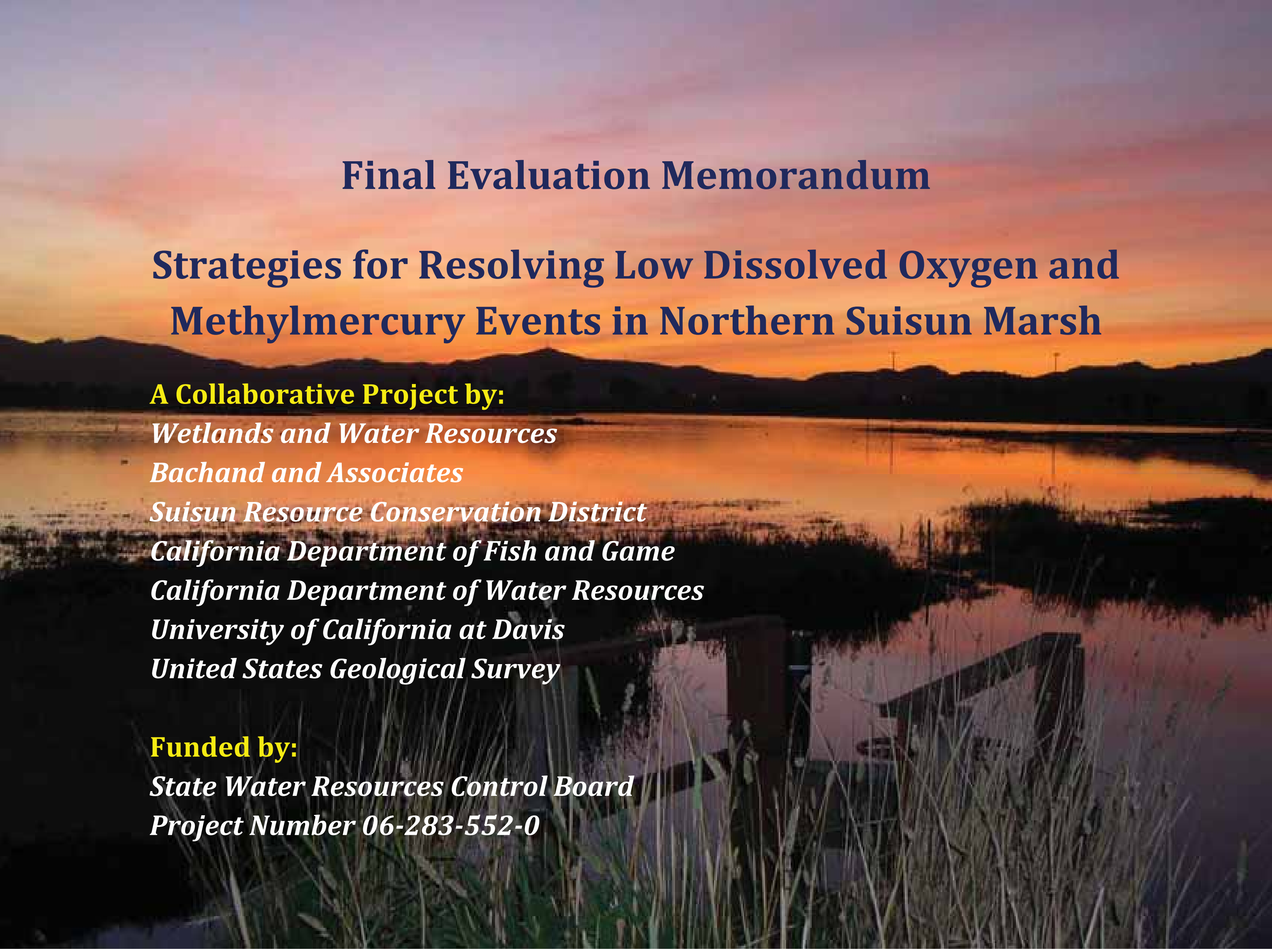

Final Evaluation Memorandum

Strategies for Resolving Low Dissolved Oxygen and Methylmercury Events in Northern Suisun Marsh

A Collaborative Project by:

Wetlands and Water Resources
Bachand and Associates
Suisun Resource Conservation District
California Department of Fish and Game
California Department of Water Resources
University of California at Davis
United States Geological Survey

Funded by:

State Water Resources Control Board
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May 2011

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Strategies for Resolving Low Dissolved Oxygen and Methylmercury Events in Northern Suisun Marsh
May 2011

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Available for download at: www.swampthing.org or contact Wetlands and Water Resources at (415) 457-0250.

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Cover photograph: Dan Gillenwater (Wetlands and Water Resources), Nov 28, 2007

EXECUTIVE SUMMARY

The purpose of the project is to improve our understanding about best management practices that can be utilized on diked managed wetlands in Suisun Marsh for reducing the occurrence of low dissolved oxygen (DO) and high methylmercury (MeHg) events associated primarily with fall flood-up practices. Low DO events are of concern because they can lead to undue stress and even mortality of sensitive aquatic organisms. Elevated MeHg levels are of concern because MeHg is a neurotoxin that bio-magnifies up the food chain and can cause deleterious effects to higher trophic level consumers such as piscivorous fish, birds, and mammals (including humans).

This study involved two years (2007-2008) of intensive field data collection at two managed wetland sites in northwest Suisun Marsh and their surrounding tidal sloughs, an area with prior documented low DO events. In addition, the study collected limited soils and water quality field data and mapped vegetation for three managed wetland sites in the central interior of Suisun Marsh, for the purpose of examining whether wetlands at other locations exhibit characteristics that could indicate potential for similar concerns. In Year 1 of the study, the objective was to identify the baseline conditions in the managed wetlands and determine which physical management conditions could be modified for Year 2 to reduce low DO and MeHg production issues most effectively. The objective of Year 2 was to evaluate the effectiveness of these modified management actions at reducing production of low DO and elevated MeHg conditions within the managed wetlands and to continue improving understanding of the underlying biogeochemical processes at play.

This Final Evaluation Memorandum examined a total of 19 BMPs, 14 involving modified water management operations and the remaining five involving modified soil and vegetation management practices. Some of these BMPs were previously employed and others have not yet been tested. For each BMP this report assesses its efficacy in improving water quality conditions and potential conflicts with wetland management. It makes recommendations for further study (either feasibility assessments or field testing) and whether to consider for future use. Certain previously used BMPs were found to be important contributors to poor water quality conditions and their continued use is not recommended. Some BMPs that could improve water quality conditions appear difficult to implement in regards to compatibility with wetland management; these BMPs require further elaboration and feasibility assessment to determine whether they should be field tested. In practice for any given wetland, there is likely a combination of BMPs that would together have the greatest potential to address the low DO and high MeHg water quality concerns. Consequently, this report makes no sweeping recommendations applicable to large groups of wetlands but instead promotes a careful consideration of factors at each wetland or small groups of wetlands and from that assessment to apply the most effective suite of BMPs.

This report also identifies a number of recommended future actions and studies. These recommendations are geared toward improving the process understanding of factors that promote low DO and high MeHg conditions, the extent of these problems in Suisun Marsh, the regulatory basis for the DO standards for a large estuarine marsh, the economics of BMPs, and alternative approaches to BMPs on diked managed wetlands that may address the water quality issues. The most important of these recommendations is that future BMP implementation should be carried out within the context of rigorous scientific evaluation so as to gain the maximum improvement in how to manage these water quality issues in the diked managed wetlands of Suisun Marsh.

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Acronyms

ABAG	Association of Bay Area Governments
BMP	Best Management Practice
BOD	Biological Oxygen Demand
CDFG	California Department of Fish and Game
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DWR	California Department of Water Resources
EQIP	Environmental Quality Incentive Programs (federal USDA funds available for promoting structural improvements that facilitate the implementation of conservation practices)
FSSD	Fairfield-Suisun Sewer District
MeHg	Methylmercury
mg/L	milligrams per Liter
ng/L	nanograms per Liter
MS	Montezuma Slough
SRCD	Suisun Resource Conservation District
SUVA	Specific Ultraviolet (UV) absorbance
UC	University of California
USGS	United States Geological Survey
UV	Ultraviolet
WWR	Wetlands and Water Resources

Acknowledgements

We would like to thank the owners of the five participating managed wetlands for volunteering use of their lands for this study, for undertaking wetland management efforts in accord with this study, and for their facilitation of data collection activities.

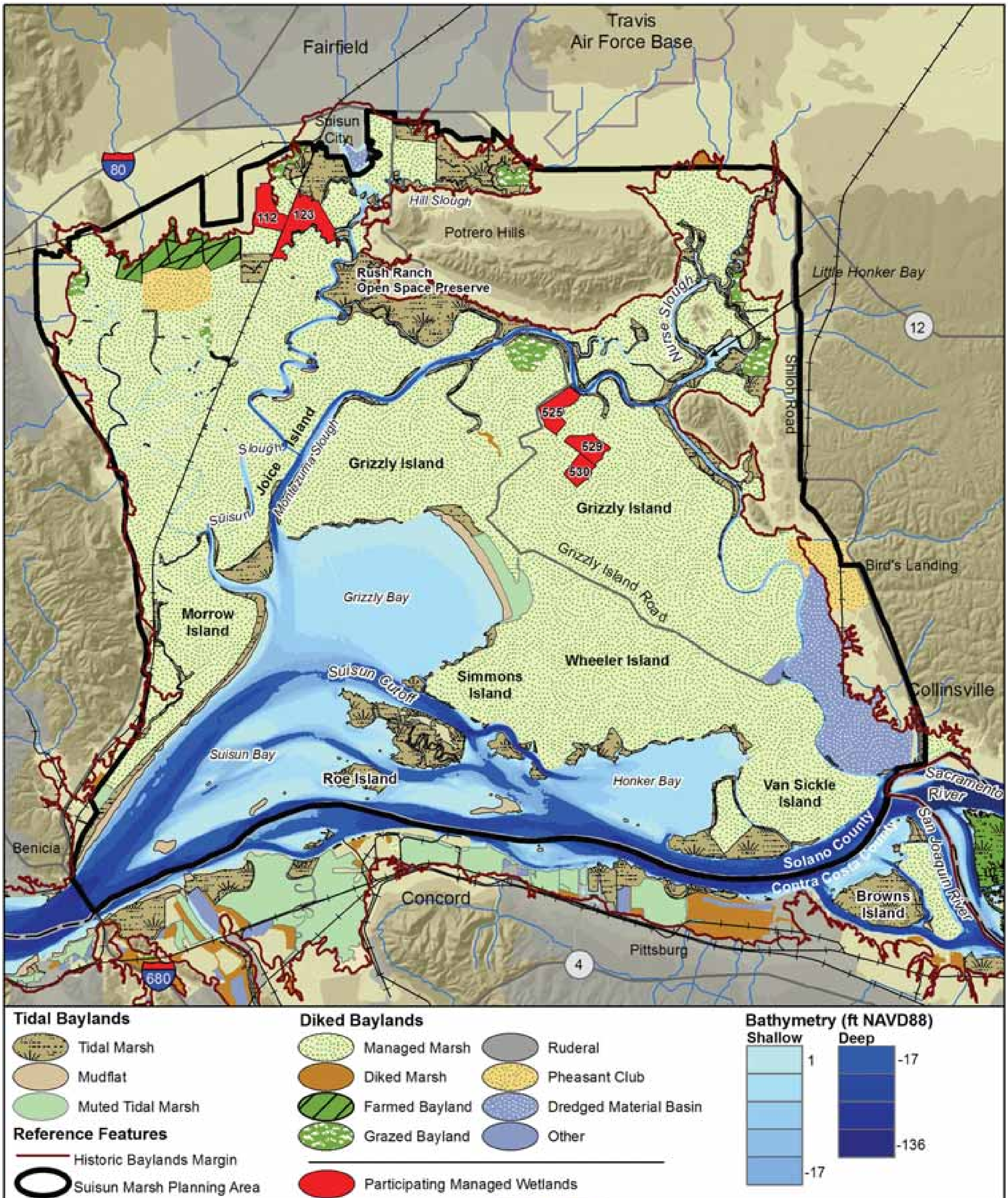
Walnut Creek Gun Club (Wetland 123) – Walnut Creek Gun Club, Inc.
Suisun Farms (Wetland 112) – Tim Egan
Balboa Farm (Wetland 525) – Steve and Hayden Markstein
Sprigsville Ranch (Wetland 529) – Terry Connolly
Bul-Rush Farms (Wetland 530) – Todd Cerini

1 Introduction

The purpose of the project is to improve our understanding about best management practices that can be utilized on diked managed wetlands in Suisun Marsh for reducing the occurrence of low dissolved oxygen (DO) and high methylmercury (MeHg) events associated primarily with fall flood-up practices. Low DO events are of concern because they can lead to undue stress and even mortality of sensitive aquatic organisms. Elevated MeHg levels are of concern because MeHg is a neurotoxin that bio-magnifies up the food chain and can cause deleterious effects to higher trophic level consumers such as piscivorous fish, birds, and mammals (including humans).

This study involved two years (2007-2008) of intensive field data collection at two managed wetland sites in northwest Suisun Marsh and their surrounding tidal sloughs, an area with prior documented low DO events (**Figure 1**). In addition, the study collected limited soils and water quality field data and mapped vegetation for three managed wetland sites in the central interior of Suisun Marsh, for the purpose of examining whether wetlands at other locations exhibit characteristics that could indicate potential for similar concerns. In Year 1 of the study, the objective was to identify the baseline conditions in the managed wetlands and determine which physical management conditions could be modified for Year 2 to reduce low DO and MeHg production issues most effectively. The objective of Year 2 was to evaluate the effectiveness of these modified management actions at reducing production of low DO and elevated MeHg conditions within the managed wetlands and to continue improving understanding of the underlying biogeochemical processes at play.

The purpose of this report is to summarize the results of our study, present our recommended best management practices (BMPs) for reducing the contribution of diked managed wetlands to low DO events and MeHg loading in Suisun Marsh, and describe future studies that will be necessary to adequately understand the issues and formulate comprehensive solutions.



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Data sources: USGS (2009), TIGER (2000), GAP (1998), Eco Atlas (1998), DWR (Various), CDFG (2006-2007)
Produced by WWR, January 2011
map file: participating-wetlands_Suisun_AP_1119_2011-0128lee.mxd

WETLANDS AND WATER RESOURCES

PARTICIPATING WETLANDS

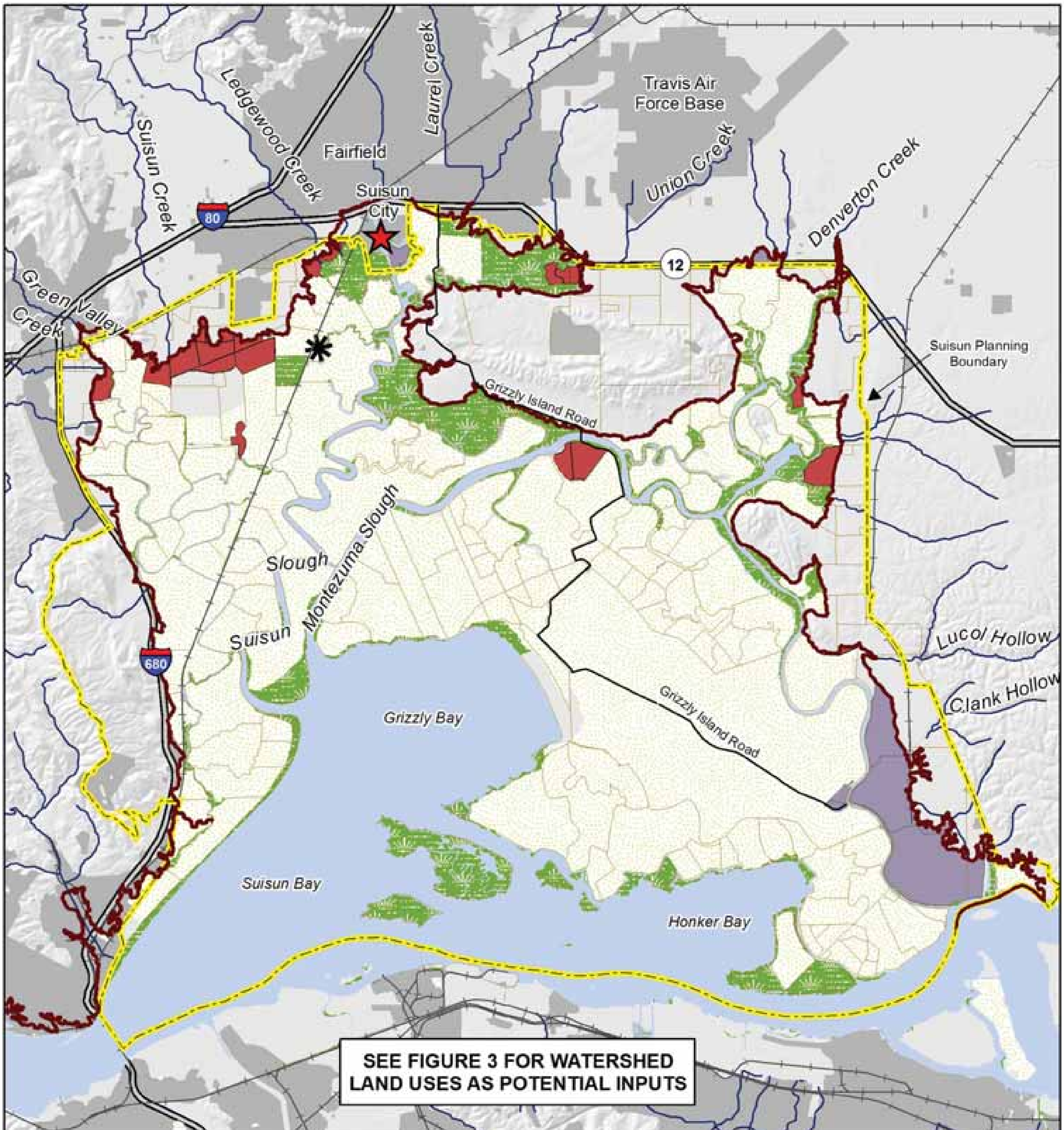
Suisun Low DO and MeHg Project
Solano County, California
SWRCB Project #06-283-552-0

January 2011	Project No. 1119	**Figure 1**

1.1 Problem Statement

Significant depressions in dissolved oxygen concentrations (DO sags) have been observed at certain times of the year in the Peytonia, Boynton, Suisun, and Goodyear Sloughs of Suisun Marsh (O'Rear and Moyle 2010, Schroeter and Moyle 2004). The observed DO sags appear to coincide in both time and space with the fall flood-up and discharge cycles of the diked managed wetlands that border these small, dead-end sloughs. Other factors that may contribute to low DO in Suisun Marsh, including storm water runoff from adjacent urbanized, military, agricultural and grazed open space lands (there is no stormwater treatment), nutrient-enriched wastewater from the Fairfield-Suisun Sewer District Wastewater Treatment Plant (regulated by NPDES permit), nearby tidal marshlands, warm water temperature, possibly illegal waste from boats in the Suisun City marina (though regulated relies upon individual compliance), and from agricultural activities in the watershed upstream of Suisun Marsh. **Figure 2** displays the distribution of these potential local inputs and **Figure 3** shows the watershed land uses as potential inputs to the low DO issue in Suisun Marsh. Except for the treatment plant discharges, the extent and seasonal variability of these contributions are not known.

The low DO sags can be persistent, and at times cover several kilometers slough habitat in northwestern Suisun Marsh (Schroeter and Moyle 2004). These low DO events can also be accompanied by elevated concentrations of MeHg, as this compound is thought to be produced in association with bacterial sulfate reduction (Compeau and Bartha 1985; Gilmour et al. 1992), a process favorable in low DO environments. Over the past 20 years, low DO and MeHg conditions have received attention from several researchers and management agencies. The current state of knowledge on the issue is presented below.



Potential Factors in Low DO Events in Perimeter Sloughs of Suisun Marsh:

- Marina
- Tertiary Treated Wastewater
- Urbanized Areas
- Creeks & Open Storm Drains
- Existing Tidal Marsh
- Diked Marsh
- Agriculture
- Other

Reference Features:

- Railroad
- Historic Bayland Margin
- Property Ownership Boundaries

1:150,000 (1" = 12,500' at letter layout)

0 1 2 mi

0 2 4 km

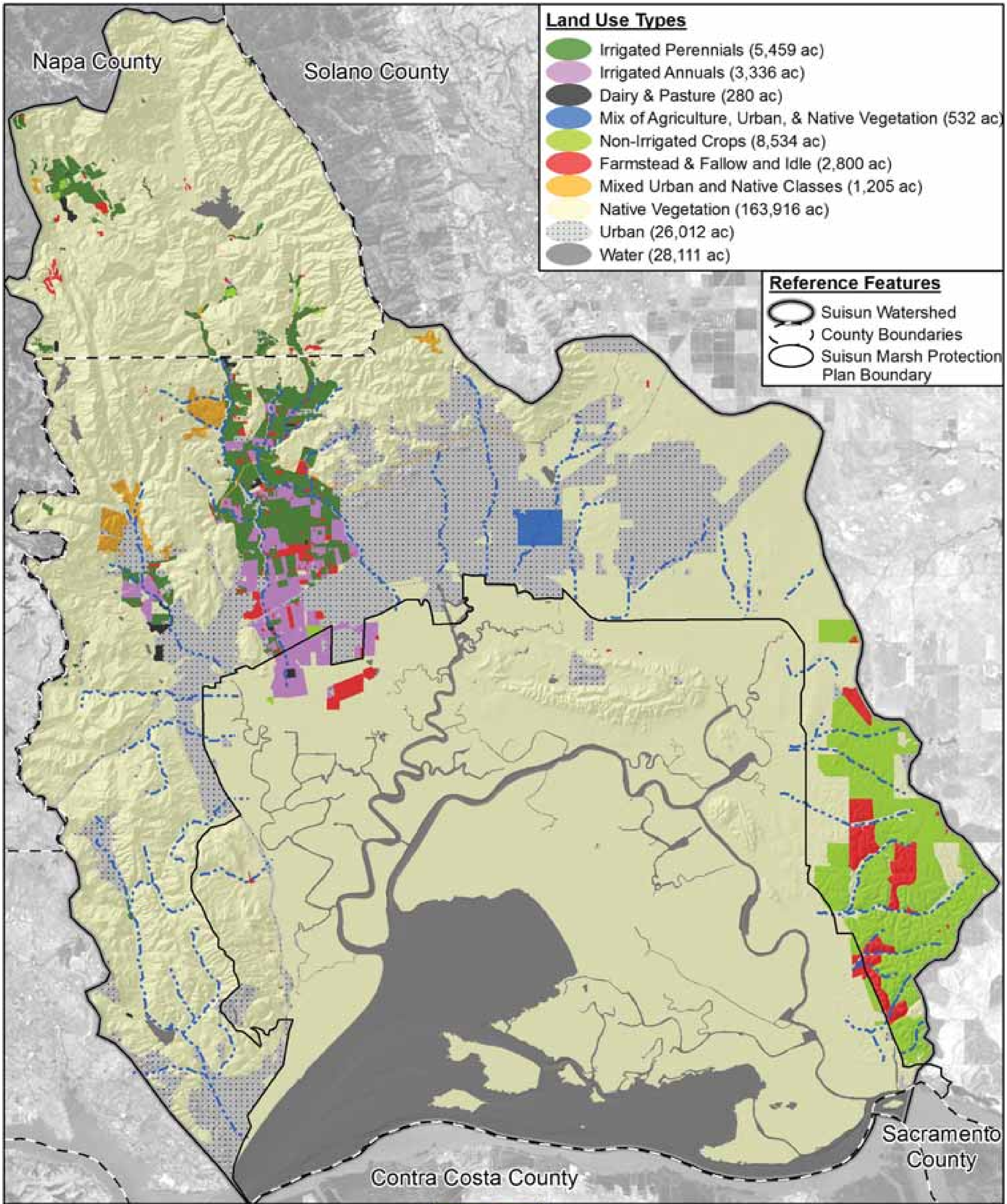
Data sources: creeks, historic margin (SFEI 1998); tidal bays and sloughs (DFG & USGS various years, SFEI 1998)
Produced by WWR, April 2011
map file: loadings-local_Suisun_AP_1119_2011-0426lee.mxd

WETLANDS AND WATER RESOURCES

LOCAL LAND USES AS POTENTIAL LOADINGS INTO SUISUN MARSH

Suisun Low DO and MeHg Project
Solano County, California
SWRCB Project #06-283-552-0

April 2011 | Project No. 1119 | **Figure 2**



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0 1.5 3 mi

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Data Sources: land use (DWR 2007); watershed (SFBRWQCD 2003); SMPP (WWR 2011)
Produced by WWR, April 2011
Map File: loadings-watershed_Suisun_AP_1119_2011-0426lee.mxd

WETLANDS AND WATER RESOURCES

WATERSHED LAND USES AS POTENTIAL LOADINGS INTO SUISUN MARSH

Suisun Low DO and MeHg Project
Solano County, California
SWRCB Project #06-283-552-0

April 2011	Project No. 1119	Figure 3

1.1.1 History of Low Dissolved Oxygen Conditions in Suisun Marsh

Suisun Marsh water quality concerns were first noted by UC Davis researchers in Peytonia Slough and Goodyear Slough as early as 1993 (Schroeter and Moyle 2004). In fall of 1999, researchers began measuring and reporting low DO sags in detail in response to increased fish mortality observed during monthly sampling activities. Low DO events accompanied by abnormally high levels of fish mortality (fish kill) were documented in the fall of 1999, 2001, and 2003 (Robert Schroeter, personal communication). In October 2004 a widespread fish kill was observed across several kilometers of Peytonia, Boynton, Goodyear, and Suisun Sloughs that coincided with managed wetland low DO discharges. Fishes including Sacramento splittail (*Pogonichthys macrolepidotus*), Sacramento sucker (*Catostomus occidentalis*), chinook salmon (*Oncorhynchus tshawytscha*), striped bass *(Morone saxatilis),* various introduced gobies, and common carp (*Cyprinus carpio*) were found dead in areas where low DO events occurred (Schroeter and Moyle 2004). Investigations are not known to have taken place to determine whether there may have been other contributing factors to this fish kill. Fish kills can be difficult to detect and the monthly sampling frequency by UC Davis researchers means that other events may have gone unnoticed. Fish mortality was reported in Hill Slough and the Suisun City Marina in fall 2009, but no water quality data from that time period are available to verify if low DO conditions were the cause. The UC Davis sampling program observed a low DO event in upper Goodyear Slough in October 2009 that was accompanied by 100% mortality of fishes captured in their trawls (O'Rear et al. 2010). That event may have reflected a confluence of unrelated operations on multiple diked and one tidally restored property including failure of water control structures originally servicing the tidally restored site (Steve Chappell, pers. comm.).

There is a seasonal component to the DO sags with both early summer and fall DO sag events. The magnitude of many of these DO sag events, especially in the fall (dissolved oxygen concentrations < 2 mg/l) is sufficient to result in mortality of most fishes, invertebrates and other organisms utilizing the sloughs and waterways of Suisun Marsh and to displace surviving organisms. Even the most tolerant fishes, such as splittail, can only tolerate levels < 2 mg/l for short periods of time but they generally can detect the low levels and avoid them. Because of tidal flushing, fish populations in sloughs can usually recover from severe low DO events, at least partially, in 2-4 months (UCD Suisun Marsh fish data). **Table 1** below lists the observed DO tolerances for species commonly observed in Suisun Marsh.

Table 1. Low Dissolved Oxygen Tolerances of Suisun Marsh Fishes and Macroinvertebrates

Source: see Appendix D.

Category	Definition	Order of Low DO Tolerance [1]
Specialists	Species that can spend extended periods of time (< 2 hrs) in water with DO levels < 2 mg/l. They often have alternative mechanisms for obtaining oxygen	Western mosquitofish Black Sea jellyfish Black bullhead Common carp White catfish Goldfish Sacramento splittail
Tolerant species	Species that regularly occur in water with dissolved oxygen levels of 2-5 mg/l. Such water may not be optimal but is mostly not lethal (but depends on temperature).	Threespine stickleback Prickly sculpin Shimofuri goby Mississippi silverside Bay shrimp Sacramento sucker Yellowfin goby Juvenile striped bass Threadfin shad Adult tule perch Black crappie Siberian prawn Calanoid copepods Opposum shrimp White sturgeon
Non-tolerant species	Species that are rarely found in water that has dissolved oxygen levels less than 5-7 mg/l; they actively avoid or die in water much below saturation levels. For many species this means the water is fairly cold as well (<20°F). Such species actively avoid water with lower DO levels.	Adult striped bass Staghorn sculpin Juvenile tule perch American shad Cladocera Delta smelt Longfin smelt Steelhead Chinook salmon Northern anchovy Pacific herring

[1] Species listed in approximate order of tolerance to low dissolved oxygen levels under conditions found in Suisun Marsh. For some species, laboratory tolerances may be higher than observed in the Marsh. There are also strong interactions among DO, salinity, and temperature which may affect apparent low DO tolerance. Thus, assignments of fish to places on the list should be regarded as approximate.

1.1.2 Peytonia and Boynton Sloughs Study Area

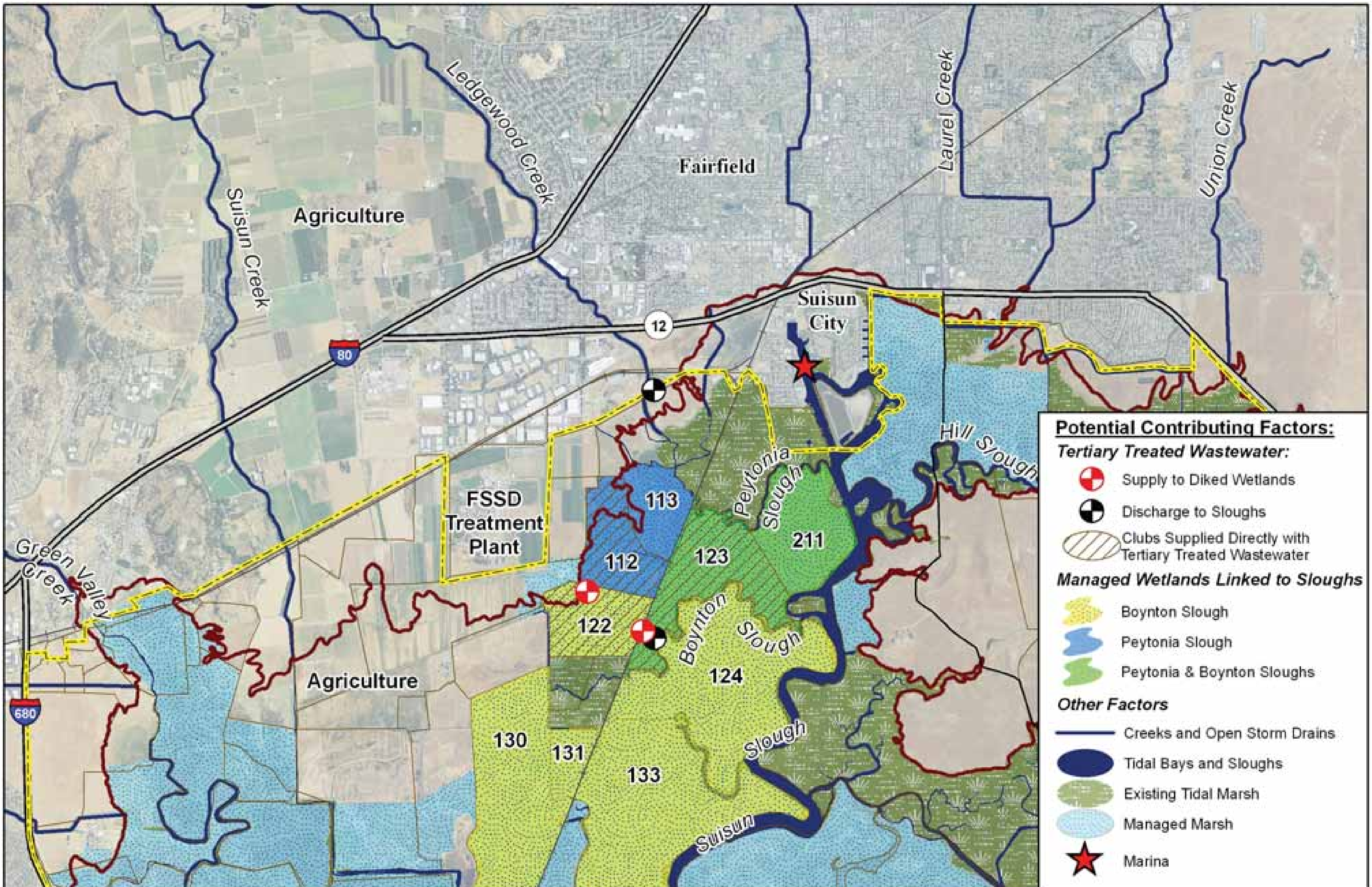
This study focused on Peytonia and Boynton sloughs because these two sloughs have exhibited low DO problems more frequently, for longer periods, and with some of the lowest DO levels. Here we provide an overview of these two sloughs, the diked managed wetlands that do and can connect to them, and watershed connectivity (**Figure 4**).

Peytonia Slough

Peytonia Slough is the northern of the two study area sloughs. Its northern side is flanked by tidal marsh within the Peytonia Slough Ecological Reserve (DFG) that extends from Suisun Slough west across the railroad to the upland edge. Its southern side is bounded by Wings Landing (Wetland 211) at its confluence with Suisun Slough and Walnut Creek (Wetland 123) that extends up to the railroad. Once west of the railroad, Tule Farms Club (Wetland 113) and Suisun Farms (Wetland 112) link to Peytonia Slough. Also once west of the railroad, Peytonia Slough connects to Ledgewood Creek, a large stormwater outfall draining much of western Fairfield, and a second smaller stormwater outfall draining agricultural and industrial lands. The FSSD Treatment Plant has a new discharge into the upper reaches of Peytonia Slough the operations of which vary and have some flexibility. Peytonia Slough is about 80 feet wide at its mouth with Suisun Slough, about 60 feet wide at the railroad after which it drops to 20-30 feet in width depending upon tributary arm.

Boynton Slough

Boynton Slough is the southern of the two study area sloughs. Its northern side is flanked by Wings Landing (Wetland 211) at its confluence with Suisun Slough and Walnut Creek (Wetland 123) west to the railroad. Along its southern border the entire distance between Suisun Slough and the railroad is Fat Hen Farm (Wetland 124). If existing water conveyance ditches are used, it can connect hydrologically to Shelldrake Duck Club (Wetland 133) to its immediate south. Once west of the railroad, Boynton Slough enters restored tidal marsh in the Grey Goose Unit of the DFG Reserve. Either through or around this marsh, Boynton Slough connects to three additional managed wetlands: Gray Goose (Wetland 122), Track Property (Wetland 130), and Jacksnipe Gun Club (Wetland 131). Further upstream from these wetlands are diked lands and adjacent uplands in agricultural use and containing stormwater and irrigation ditches that can connect with these upper reaches of Boynton Slough. The FSSD Treatment Plant has a direct discharge into Boynton Slough a short distance east of the railroad and its discharge is used in Wetland 122 which then drains into Boynton Slough. FSSD has operational variability and some flexibility with its discharges.



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Historic Bayland Margin
Suisun Marsh Property Ownership Boundaries
Suisun Marsh Protection Plan Boundary

N W E S

Data sources: air photo (NAIP 2009); tidal waters (USGS, CDFG various years); tidal marsh, Suisun Creeks, and historic bayland margin (SFEI 1998)
Produced by WWR, April 2011
Map file: Contrib-Factors_Pey-Boy-Sloughs_AL_1119_2011-0428ekc.mxd

WETLANDS AND WATER RESOURCES

POTENTIAL LOW DO CONTRIBUTING FACTORS
PEYTONIA AND BOYNTON SLOUGHS

Suisun Low DO and MeHg Project
Solano County, California
SWRCB Project #06-283-552-0

April 2011	Project No. 1119	Figure 4

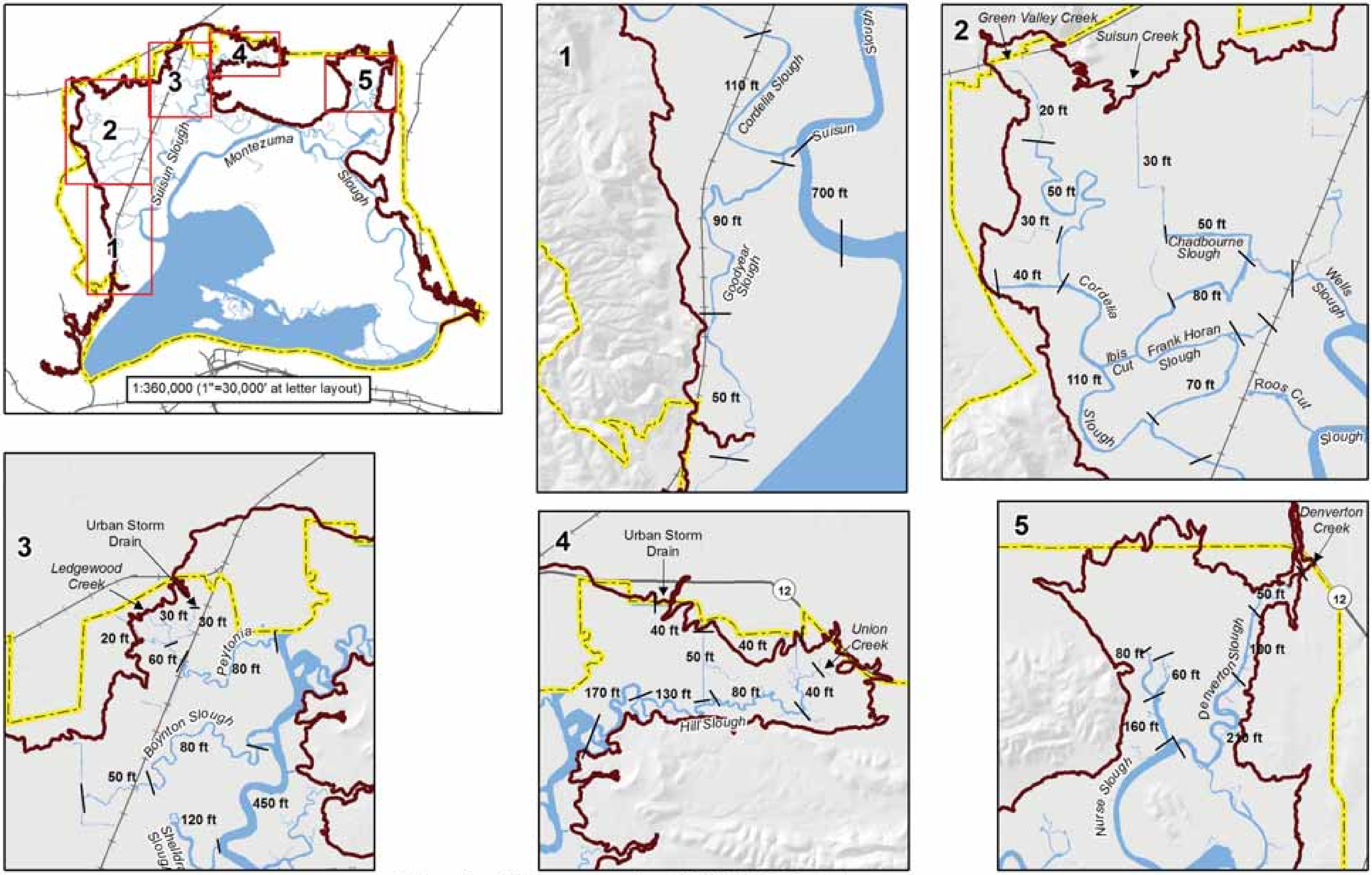
1.1.3 Spatial Context of Study Areas

Low DO and elevated MeHg events have been observed in Peytonia, Boynton, and Goodyear Sloughs, which are tributaries to Suisun Slough in western and northwestern Suisun Marsh (O'Rear and Moyle 2010; Schroeter and Moyle 2004). Suisun Slough itself has also experienced low DO events co-occurring with those in the tributary sloughs (Schroeter and Moyle 2004). There are several factors which may contribute to the propensity for these particular sloughs to develop low DO conditions including slough size (related to tidal exchange rates) and the various hydrologic inputs to the sloughs (adjacent watersheds, sewage treatment plant effluent, managed wetlands, and tidal marshes). These contributing factors are described in this section.

Slough Size

The impacted sloughs are all tributaries to Suisun Slough. As such, these sloughs are far smaller in size (width and depth) than Suisun Slough. Small sloughs are more at risk for developing low DO conditions than larger sloughs due to their reduced ability for internal mixing and tidal exchange with water in larger bayward sloughs. "Dead-end" sloughs, which have little or no hydrologic connection at their upstream ends, may be at the highest risk for developing these problems. **Figure 5** displays the average reach widths of sloughs around Suisun Marsh.

Peytonia and Boynton Sloughs are approximately 80 ft wide at their junction with Suisun Slough; Suisun Slough is approximately 450 ft wide at these confluences. Peytonia Slough continues the 80-ft width for about 1¾ miles upstream of Suisun Slough then narrows above the railroad tracks down to 20-30 ft at its upper limits. Boynton Slough retains its roughly 80-foot width for more than 2.5 miles before tapering down close to the railroad tracks. Goodyear Slough is slightly larger than Peytonia and Boynton Sloughs. Goodyear Slough is approximately 90 ft wide for about 2.5 miles upstream of that confluence. Suisun Slough is approximately 700 ft wide at its confluence with these two sloughs. These sloughs are smaller than other perimeter sloughs in northern and northeastern Suisun where low DO problems have not been reported. Hill Slough is roughly 170 ft wide near its confluence with Suisun Slough and tapers down below 80 ft only at its eastern end. Nurse and Denverton Sloughs in the northeast both are well above 100 ft in width for much of their lengths.



*slough widths measured on 2009 NAIP air photo

Suisun Marsh Protection Plan Boundary

Historic Bayland Margin

Railroad

Data sources: tidal sloughs (CDFG, USGS various years); railroad (USGS); Historic Margin (SFEI 1998)
Produced by WWR, April 2011
map file: perimeter-slough-widths-suisun_AL_1119_2011-0428ekc.mxd

1:90,000 (1" = 7,500' at letter layout)
*applies to all frames except where noted

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N W E S

WETLANDS AND WATER RESOURCES

WIDTH OF PERIMETER SLOUGHS IN SUISUN MARSH

Suisun Low DO and MeHg Project
Solano County, California
SWRCB Project #06-283-552-0

April 2011	Project No. 1119	Figure 5

Hydrology

Up to four external hydrologic sources reach Peytonia, Boynton, and the several other sloughs along the periphery of Suisun Marsh: tides (dominant), watershed runoff (seasonally important), the FSSD Wastewater Treatment Plant (Boynton Slough mainly, Peytonia Slough occasionally), and direct rainfall. In addition, operation of the many diked wetlands exerts a seasonally very strong influence on slough hydrology. Tidal marshes along the sloughs can also have an impact on the hydrology of the systems. **Figure 2** displays the marsh-wide distribution of these potential hydrologic inputs, while **Figure 4** shows a focused view of these inputs in the northwest corner of the Marsh where this study was focused.

These hydrologic inputs can be direct contributors of low DO water or can contribute nutrients and organic matter to the sloughs that contributes to production of low DO events. Nutrients, primarily nitrogen and phosphorus, can contribute to low DO events by stimulating algae and plant growth within the receiving water body (Goldman and Horne 1994) that contributes to BOD as it decays. Likewise, organic matter inputs from surrounding sources will directly contribute to the BOD of the water body.

Tides. Tides are the dominant hydrologic force in Suisun tidal sloughs. Suisun and Montezuma sloughs are the two largest sloughs conducting the tides throughout Suisun. Off these two main sloughs branch numerous sloughs around the outer margins of Suisun Marsh. Peytonia and Boynton Sloughs, the main focus of this study, are located in northwest Suisun Marsh off Suisun Slough (**Figure 4**). Suisun Marsh experiences mixed semi-diurnal tides, with twice-daily high and low tides of about 5 feet in range. The mixed, semi-diurnal tidal regime has a strong variation in tide range between spring tides (large tide range) and neap tides (small tide range) conditions. The spring-neap tidal cycle tracks moon phase and thus has a roughly two-week period. The magnitude of spring and neap tides also tracks seasonality, with summer and winter spring tides larger than spring and fall spring tides. The result is variation in daily tidal ranges of as little as 2-3 ft during neap tides to 8 ft during spring tides. Boynton Slough tidal flows range between about -800 and +1200 cfs while Peytonia Slough tidal flows range between about -700 and +800 cfs (Appendix G), varying with three time scales of tidal processes: the daily unequal high and low tides, the biweekly spring-neap tides, and the quarterly seasonal tide (Gilmour et al. 1971).

Surrounding Watersheds. Several creeks enter Suisun Marsh. The largest and most urbanized watersheds are to the north of Suisun Marsh and include Green Valley Creek, Suisun Creek Ledgewood Creek, Laurel Creek, Union Creek, and Denverton Creek along with several unnamed storm channels (Figure 2). All but Denverton Creek discharge into Suisun Slough. In addition, the hills west of Highway 680 contain several small drainages the northern ones of which drain ultimately to Suisun Slough. All the impacted sloughs receive some degree of hydrologic input from the surrounding local developed watershed during the rainy season. Though the USGS quad sheets show all these streams as seasonal, some may have flow well past the rainy season due to urban runoff (landscaping drainage, etc.); this study did not investigate the hydrology of any of these streams.

Peytonia Slough receives watershed inputs from two sources: Ledgewood Creek and an unnamed open storm drain. Ledgewood Creek is a small stream that drains a watershed of approximately 11,300 acres north of Suisun Marsh and flows along the west edge of the City of Fairfield and the east side of cultivated agricultural lands in lower Suisun Valley prior to meeting with Peytonia Slough. The watershed contains agricultural, urban, and open space lands. The unnamed storm drain drains the center of Fairfield along Pennsylvania Avenue; we have not researched the full extent of its drainage catchment nor the details of land uses within it. Boynton Slough receives no significant watershed inputs; a portion of lowlands sod farm and the industrial areas in the northwest corner of Suisun Marsh, between Suisun and Ledgewood creeks to highway 12, drains into Boynton Slough.

Sewage Treatment Effluent. The Fairfield-Suisun Sewer District (FSSD) Wastewater Treatment Plant discharges a majority of its tertiary treated effluent to Boynton Slough (**Figure 4**). A smaller discharge point exists on Ledgewood Creek in the case of high effluent flows or failure of the primary discharge point to Boynton Slough. A portion of these discharges enter directly into three managed wetlands: Wetlands 112 and 123 (both subjects of this study) and Wetland 122. Sewage treatment effluent can contain nutrients and BOD levels that can contribute to low DO problems in receiving water bodies. Tertiary treatment standards for FSSD require treatment levels shown in **Table 2**.This study investigates the hydrology and water quality of the tertiary treated effluent from FSSD to assess its effects on water quality at its discharge points and in the adjacent sloughs.

Table 2. NPDES requirements for FSSD (NPDES No. CA0038024)

Source: RWQCB 2009

Parameter	Units	Effluent Limitations				
		Average Monthly	Average Weekly	Max Daily	Intantaneous Min	Intantaneous Max
Biochemical Oxygen Demand (BOD)	mg/l	10	15	20	--	--
Total Suspended Soilds (TSS)	mg/l	10	15	20	--	--
Oil and Grease	mg/l	--	--	10	--	--
pH	s.u	--	--	--	6.5	8.5
Turbidity	NTU	--	--	10	--	--
Total Residual Chlorine	mg/l	--	--	--	--	0

Managed Wetland Discharges. All of the impacted sloughs are connected to managed wetlands. These wetlands can hydrologically impact the sloughs during periods in which the wetlands are flooded or drained. In the fall, some wetland managers flood their wetlands to fall management levels and circulate water throughout the season, while other managers flood their properties to half or full capacity and then drain them off prior to re-flooding for the fall management season. The purposes of this initial flood-drain cycle are to minimize conditions that are thought to cause low DO events (see Section 1.2.4, below) and observe regulatory requirements for vector control. Most managers also perform a series of flood-drain cycles after the end of the fall management season (February through June) to leach salts from the soils. When flooding occurs, the volume of the wetlands that are being flooded adds greatly to the tidal prism of the sloughs, increasing the volume of water that passes through the sloughs. This impact is greatest in the fall because water brought onto the wetlands is needed to saturate the soils that were dried out during the summer months. When the wetlands are drained, they can contribute low DO water and BOD to the receiving slough. Four wetlands (112, 113, 123, and 211) with a total area of 980 ac are connected to Peytonia Slough, while six wetlands (122, 123, 131, 124, 130 and 133) with a total area of 3,000 ac are connected to Boynton Slough (**Figure 4**). Under normal operations, Wetland 123 will draw water from Peytonia Slough and FSSD and discharge to Boynton Slough.

Tidal Marshes. Though fully tidal marshes are not common in Suisun Marsh, Peytonia and Boynton Sloughs both have fully tidal marshes connected to them. The 630-ac Peytonia Slough Ecological Reserve is located along Peytonia Slough, while the smaller 150 ac Grey Goose unit of Grizzly Island Wildlife Area is connected at the terminal end of Boynton Slough. Tidal marshes are productive systems that contribute organic matter to the receiving water body and thus can increase the BOD of the system.

1.1.4 Dissolved Oxygen Standards in Suisun Marsh

The Basin Plan for San Francisco Bay (which includes Suisun Marsh) states that the minimum DO concentration for all tidal waters upstream of the Carquinez Strait Bridge will be 7.0 mg/l with the three-month median DO concentration not less than 80% of the DO concentration at saturation (RWQCB 2007, p.58). The DO concentration at saturation varies throughout the year as oxygen solubility is water temperature dependent with DO concentrations decreasing as water becomes warmer.

1.1.5 Previous Efforts to Manage Low Dissolved Oxygen Events

As awareness of low DO events in Suisun Marsh grew, these concerns were brought to the attention of the State Water Resources Control Board (SWRCB), the Suisun Resource Conservation District (SRCD), the California Department of Fish and Game (CDFG), and the Department of Water Resources (DWR). In response, water quality monitoring was conducted in 2006 and 2007 by SRCD and CDFG in compliance with Condition 1.b. of the 2006 National Marine Fisheries Service Biological Opinion. SRCD also began working with private landowners to minimize or avoid low DO events and mitigate MeHg releases through improved water management and modification of vegetation management and manipulation. Guided by these initial efforts, more systematic water quality monitoring of additional parameters has been conducted since 2006 in northwest Suisun Marsh sloughs by UC Davis (Center for Watershed Science) and SRCD.

Past research and outreach efforts have resulted in a number of recommendations by the SRCD for Suisun wetland management practices:

- Landowners with mosquito production or low DO problems were recommended to conduct an early flood-drain cycle prior to bringing ponds to fall management level.
- Once at fall management level, landowners were recommended to circulate water at highest rate possible until temperatures cool (mid-November).

- Landowners were recommended to avoid wetland discharges to dead end drainage sloughs and to redirect discharges to larger sloughs, in order to maximize mixing with tidal waters and thus minimize low DO sags.
- Implementing water management activities to discourage broadleaf plant growth and encourage physical manipulation of this vegetation prior to fall flooding.

In response to these recommendations, many landowners have made changes to their management practices. Many now flood to fall management levels as late as possible in order to minimize flooded conditions during late summer and early fall when higher air temperatures can occur. Decomposition rates increase as temperature increases and therefore temperature is considered a key factor leading to high BOD load from organic matter decomposition. Many landowners have also changed vegetation management methods by employing chemical control of broadleaved plants during spring and mowing or light discing of broadleaved plants during summer. Adaptive implementation of new management practices by landowners enables refined understanding of the nature and extent of low DO events and, through this project, the development of solutions that are compatible with landowner wetland management objectives, regional land use, and broader ecological issues.

Since implementing these management changes there seems to have been a reduction in the occurrence and severity of fish kills within Suisun Marsh. However, as noted above, the monthly sampling frequency by UC Davis researchers may allow for events to go unnoticed if sampling does not take place during or immediately after low DO discharge events (Peter Moyle, personal communication).

1.2 Study Objectives

The objectives of this study are to (1) determine baseline water quality and environmental (soil, vegetation, hydrology) conditions in the studied managed wetlands, (2) implement and evaluate the effectiveness of one or more management strategies to reduce the production of severely low DO events associated with managed wetlands operations, and (3) transfer successful new management practices to the broader managed wetlands community in Suisun Marsh including adaptive management elements for practices that could benefit from further refinement. In addition, reduction of low DO events may also result in a decrease in MeHg concentrations within the managed wetlands and reduce MeHg loading to the surrounding waters. The intended outcomes of this project are improvements to the aquatic ecosystem and to wildlife and humans that consume the fish and other aquatic organisms in Suisun Marsh while at the same time maintaining productive managed wetland habitats for resident and migratory wildlife species.

This focused study is being carried out in two clusters of managed wetlands in Suisun Marsh (**Figure 1**). The northwest wetland cluster, which includes Suisun Farms (Wetland 112) and Walnut Creek Gun Club (Wetland 123), is the focus in this study and is where the bulk of our data collection efforts take place. These wetlands were chosen for the following reasons: (1) landowner willingness to participate and modify operations to accommodate the needs of this study, (2) proximity to documented low DO problem areas, (3) potential for modified management practices to offer a demonstrable improvement in water quality, and (4) tractable hydrologic configuration to facilitate cost effective and meaningful analyses. The central wetland cluster, which includes Balboa Farms (525), Sprigsville Ranch (529), and Bulrush Farms (530), is the location of more general background data collection aimed at establishing baseline conditions elsewhere in greater Suisun Marsh. A complete description of the physical, hydrological, biological, and management characteristics of these managed wetlands can be found in Appendix **A** of this document.

1.3 Data Collection Approach

Data collection for this project occurred over two wetland management seasons (Year 1 and Year 2). Year 1 data collection spanned from September 2007 to April 2008, while Year 2 data collection spanned from September 2008 to November 2008. The data collection approaches for each year are described individually below. The project monitoring plan (WWR et al., 2007) contains additional information on the sampling and analysis methods. The data collection activities for Year 1 and Year 2 are summarized in **Table 3**.

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Table 3. Summary of Data Collection Activities

Sample Site Designation	General location	Comments	Station ID - Original	Station ID - Final	Static Location Coordinates	Year-1	Year-2
Continuous water quality and depth (11 locations)	Northwest wetlands (2 sites)	Supports Wetland Water Quality and Stage monitoring. Multi-parameter data sondes (YSI 6600s) deployed at these 8 managed wetland input/discharge exchange points. In 2008 new stations were installed in dub interiors and some preimeter stations were abandoned	112-CWQ-1	112-CWQ-1	38.21761 N 122.05908 W	YES	YES
			112-CWQ-2	112-CWQ-2	38.21807 N 122.06038 W	YES	YES
			112-CWQ-3	112-CWQ-4	38.21533N 122.06409W	NO	YES
			123-CWQ-1	123-CWQ-1	38.21746 N 122.05473 W	YES	YES
			123-CWQ-2	123-CWQ-2	38.22191 N 122.05093 W	YES	NO
			123-CWQ-3	123-CWQ-3	38.22063 N 122.04638 W	YES	YES
			123-CWQ-4	123-CWQ-4	38.21034 N 122.04305 W	YES	YES
			123-CWQ-5	123-CWQ-5	38.21506 N 122.04773 W	YES	NO
			123-CWQ-6	123-CWQ-6	38.21145 N 122.05477 W	YES	YES
			123-CWQ-7	123-CWQ-12	38.21960N 122.04845W	NO	YES
			123-CWQ-8	123-CWQ-15	38.21352N 122.04350W	NO	YES
Wetlands Discharge (8 locations)	Northwest wetlands (2 sites)	Discharge data supports characterizing sources of water quality constituents. Co-located with CWQ monitoring locations. THESE INSTRUMENTS WERE NEVER INSTALLED DUE TO BUDGET ISSUES	112-F-1	--	38.21636 N 122.05642 W	NO	NO
			112-F-2	--	38.21761 N 122.05908 W	NO	NO
			123-F-1	--	38.21746 N 122.05473 W	NO	NO
			123-F-2	--	38.22191 N 122.05093 W	NO	NO
			123-F-3	--	38.22063 N 122.04638 W	NO	NO
			123-F-4	--	38.21034 N 122.04305 W	NO	NO
			123-F-5	--	38.21506 N 122.04773 W	NO	NO
			123-F-6	--	38.21145 N 122.05477 W	NO	NO
Tidal Slough Water Flow measurement (ADCP) & Slough Water Quality	Peytonia, Boynton	Supports Slough Hydrodynamics and Water Quality monitoring. Accoustic Dopler Current Profiler (ADCP) instrument co-located with a YSI multi-parameter data sonde (YSI 600; DO, cond, temp, depth). In 2008, 2 additional water quality sondes were installed in Peytonia Slough	BS-F BS-CWQ	BS-F BS-CWQ	38.20928 N 122.03872 W	YES	YES
			PS-F PS-CWQ	PS-F-1 PS-CWQ-1	38.22644 N 122.03503 W	YES	YES
			PS-CWQ-2	PS-CWQ-2	38.22310 N 122.05185 W	NO	YES
			Slough	PS-CWQ-3	38.21645 N 122.0562 W	NO	YES
Wetland interior water level	Northwest wetlands (2 sites)	Provide wetland stage input data to hypsographs used to determine exchange volumes.	112-WL-1	112-WL-4	38.21533N 122.06409W	YES	YES
			112-WL-2	112-WL-5	38.21470N 122.05989W	YES	YES
			123-WL-1	123-WL-17	38.21260N 122.05637W	YES	YES
			123-WL-2	123-WL-12	38.21960N 122.04845W	YES	YES
			123-WL-3	123-WL-15	38.21352N 122.04350W	YES	YES

Table 3, Continued

Sample Site Designation	General location	Comments	Station ID - Original	Station ID - Final	Static Location Coordinates	Year-1	Year-2
Water quality grab samples at exterior and interior exchange points (Hg, SSC, DOC and OM)	All sites	Grab samples at wetland flood and discharge points support identifying water quality as enters and leaves sites and used in conjunction with time-series water quality data. Exterior grab water quality samples at the northwest sites are co-located with continuous water quality and flow monitoring.	123-GWQ-1	123-GWQ-1	38.21746 N 122.05473 W	YES	NO
			123-GWQ-2	123-GWQ-2	38.22191 N 122.05093 W	YES	NO
			123-GWQ-3	123-GWQ-3	38.22063 N 122.04638 W	YES	YES
			123-GWQ-4	123-GWQ-4	38.21034 N 122.04305 W	YES	YES
			123-GWQ-5	123-GWQ-5	38.21506 N 122.04773 W	YES	NO
			123-GWQ-6	123-GWQ-6	38.21145 N 122.05477 W	YES	YES
			123-GWQ-7	123-GWQ-7	38.20998 N 122.05907 W	YES	YES
			112-GWQ-1	112-GWQ-1	38.21761 N 122.05908 W	YES	YES
			112-GWQ-2	112-GWQ-2	38.21807 N 122.06038 W	YES	NO
			112-GWQ-3	112-GWQ-3	38.21401 N 122.06601 W	YES	YES
			525-GWQ-1	525-GWQ-1	38.17194 N 121.96344 W	YES	NO
			529-GWQ-1	529-GWQ-1	38.15656 N 121.95161 W	YES	NO
			530-GWQ-1	530-GWQ-1	38.14911 N 121.96242 W	YES	NO
			MS-GWQ	MS-GWQ	38.17048 N 121.96093 W	YES	NO
Wetland interior water grab samples (Hg, SSC, DOC and OM)	Northwest wetlands (2 sites)	Within-site grab water quality samples: - 112 6 interior locations for DOC and OM - 112 3 interior locations for MeHg and SSC - 123 10 interior locations for DOC and OM - 123 5 interior locations for MeHg and SSC	112-GWQ-4	112-GWQ-4	38.21533 122.06409	YES	YES
			112-GWQ-5	112-GWQ-5	38.21470 122.05989	YES	YES
			112-GWQ-6	112-GWQ-6	38.21645 122.05833	YES	YES
			112-GWQ-7	112-GWQ-7	38.21525 122.06190	YES	YES
			112-GWQ-8	112-GWQ-8	38.21956 122.06376	YES	YES
			112-GWQ-9	112-GWQ-9	38.22071 122.06188	YES	YES
			123-GWQ-8	123-GWQ-8	38.21603 122.05288	YES	YES
			123-GWQ-9	123-GWQ-9	38.21721 122.05241	YES	YES
			123-GWQ-10	123-GWQ-10	38.21595 122.04914	YES	YES
			123-GWQ-11	123-GWQ-11	38.21769 122.04820	YES	YES
			123-GWQ-12	123-GWQ-12	38.21960 122.04845	YES	YES
			123-GWQ-13	123-GWQ-13	38.21743 122.04430	YES	YES
			123-GWQ-14	123-GWQ-14	38.21550 122.04359	YES	YES
			123-GWQ-15	123-GWQ-15	38.21352 122.04350	YES	YES
			123-GWQ-16	123-GWQ-16	38.21420 122.05570	YES	YES
			123-GWQ-17	123-GWQ-17	38.21260 122.05637	YES	YES

Table 3, Continued

Sample Site Designation	General location	Comments	Station ID - Original	Station ID - Final	Static Location Coordinates	Year-1	Year-2
Soil grab samples (MeHg, HgT, OM)	All sites	- 112: 3 composite samples - 123: 5 composite samples - 525: 1 composite sample - 529: 1 composite sample - 530: 1 composite sample	112-SS-1	112-SS-10	38.21857 122.06158	YES	NO
			112-SS-2	112-SS-11	38.21708 122.06231	YES	NO
			112-SS-3	112-SS-12	38.21646 122.06100	YES	NO
			123-SS-1	123-SS-8	38.21608 122.05289	YES	NO
			123-SS-2	123-SS-9	38.21728 122.05238	YES	NO
			123-SS-3	123-SS-18	38.21441 122.05052	YES	NO
			123-SS-4	123-SS-19	38.21742 122.04914	YES	NO
			123-SS-5	123-SS-20	38.21742 122.04669	YES	NO
			525-SS-1	525-SS-1	38.16656 121.96714	YES	NO
			529-SS-1	529-SS-1	38.15748 121.96027	YES	NO
			530-SS-1	530-SS-1	38.14963 121.96124	YES	NO
Sample Site Designation	**General location**	**Comments**	**Station ID - Original**	**Station ID - Final**	**Static Location Coordinates**	**2007**	**2008**
Topography	Northwest wetlands (2 sites)	Survey throughout each site; produce georeferenced DEM	112 center	112 center	38.21928 N 122.06136 W	YES	NO
			123 center	123 center	38.21367 N 122.05008 W	YES	NO
Vegetation	Northwest wetlands (2 sites)	Aerial photo based assessment with focused ground truthing	112 center	112 center	38.21928 N 122.06136 W	YES	NO
			123 center	123 center	38.21367 N 122.05008 W	YES	NO
Meteorology station	Suisun Marsh	Located at Suisun Resource Conservation District headquarters	Met	Met	38.15497 N 121.97414 W	YES	NO
Biological sampling	Peytonia, Boynton, Suisun sloughs	Continuation of UC Davis-IEP long-term biological sampling, plus five added stations in Peytonia, Boynton and Suisun sloughs	SU1	SU1	38.21722 N 122.03167 W	YES	YES
			SU1B	SU1B	38.21119 N 122.0369 W	YES	YES
			SU2	SU2	38.20228 N 122.04051 W	YES	YES
			PT1	PT1	38.22196 N 122.04797 W	YES	YES
			PT2	PT2	38.22205 N 122.04378 W	YES	YES
			PT3	PT3	38.22579 N 122.03679 W	YES	YES
			BY1	BY1	38.21033 N 122.05413 W	YES	YES
			BY2	BY2	38.21394 N 122.04866 W	YES	YES
			BY3	BY3	38.21121 N 122.04466 W	YES	YES
			MZ1	MZ1	38.1726 N 121.96198 W	YES	YES
			MZ2	MZ2	38.16759 N 121.93507 W	YES	YES

Figures 6-8 display the monitoring locations in and around the northwest wetland cluster: **Figure 6** shows the data monitoring locations within Wetland 112, **Figure 7** shows those locations within Wetland 123, and **Figure 8** displays the external (slough) monitoring stations. The monitoring locations in the central wetland cluster are displayed in **Figure 9**.

1.3.1 Study Year 1 Sampling (Fall 2007 – Spring 2008)

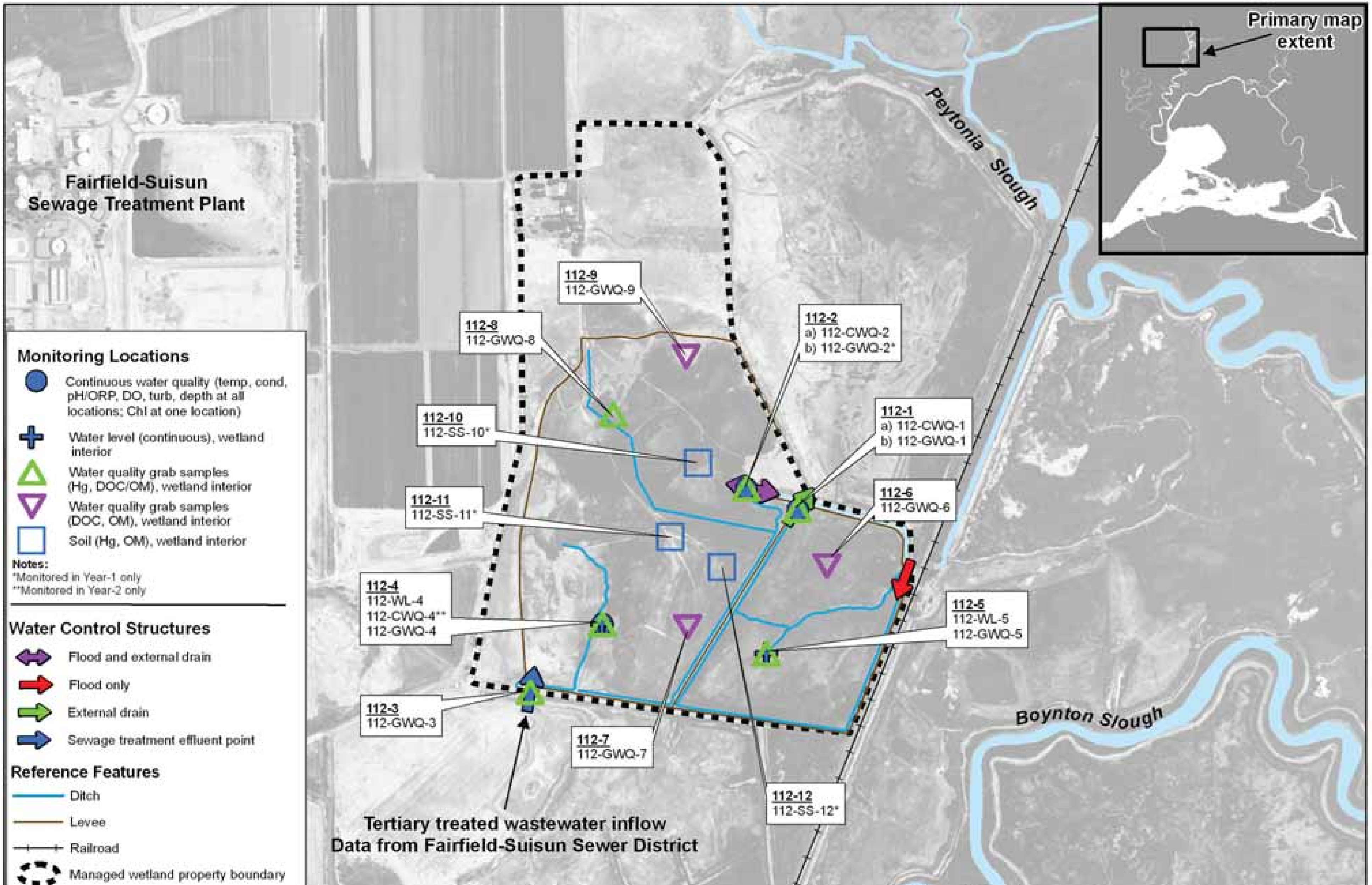
We collected a variety of data in Year 1 to determine baseline environmental conditions at the project site. The data collection spanned from September 2007 to April 2008 in order to capture the entire wetland management cycle from fall flood-up through the spring soil salt leaching cycles. The data collection approach is summarized briefly below:

- **Water quality**: We deployed continuously recording water quality instruments at major water control structures in Wetlands 112 and 123 and in Boynton and Peytonia Sloughs. In addition, water quality grab samples (for analysis of Hg/MeHg and organic matter/carbon) were made periodically at the water control structures, in the sloughs, and at sites throughout the interior of the wetlands. Periodic water quality grab samples were also made in the central wetland cluster.
- **Water level**: The continuously recording water quality instruments also recorded water level. In addition, water level sensors were placed in the interior of Wetlands 112 and 123.
- **Soil quality**: Soil samples were taken in Wetlands 112 and 123 and in the central wetland cluster and analyzed for total Hg/MeHg and organic matter/carbon.
- **Topography**: We performed a high-resolution topographic survey of Wetlands 112 and 123 and created detailed Digital Elevation Models (DEM) and contour lines of each.
- **Vegetation:** We mapped the vegetation communities on Wetlands 112 and 123 using a combination of field surveys and aerial photograph interpretation.
- **Aquatic Ecology:** UC Davis continued its monthly otter trawl sampling in the sloughs at their 21 regular stations throughout Suisun Marsh. In addition, five new stations were added to better assess the biological community in the vicinity of the study areas.

Table 4. Station ID and Characteristics

Characteristic	Club 112	Club 123	Club 525	Club 529	Club 530
Acreage					
Club total	206	281	188	150	115
Flooded	90	210	137	72	
Mean marsh elev (ft NAVD88)	4.79	3.03	NA	NA	NA
Volume at shoot level (ac-ft)	78 - 133	223 - 337	NA	NA	NA
Mean Depth at shoot level (ft)	0.71 - 1.21	0.97 - 1.47	NA	NA	NA
Water sources					
Peytonia Slough, mainstem		X			
Peytonia Slough, dead-end branch	X	X			
Boynton Slough		X			
Treatment Plant	X	X			
Montezuma Slough, fish-screened extension			X	X	X
Receiving water bodies					
Peytonia Slough, mainstem		X			
Peytonia Slough, dead-end branch	X	X			
Boynton Slough		X			
Montezuma Slough, mainstem			X		
Frost Lake (non tidal)				X	
Poleline Ditch (non-tidal)					X
Vegetation (%, acres)					
Upland	5%, 10 ac	0%, 0 ac	9%, 17 ac	7%, 10 ac	14%, 16 ac
Saline wetland	51%, 105 ac	0%, 0 ac	48%, 90 ac	52%, 78 ac	67%, 77 ac
Brackish wetland	15%, 31 ac	37%, 104 ac	11%, 21 ac	7%, 10 ac	4%, 5 ac
Freshwater wetland	1%, 3 ac	52%, 146 ac	8%, 15 ac	2%, 4 ac	3%, 4 ac
Barren			14%, 27 ac	5%, 8 ac	4%, 4 ac
No data (open water)			10%, 18 ac	27%, 40 ac	8%, 9 ac
No data (outside area of interest)	28%, 57 ac	11%, 31 ac			
Soils					
Alviso silty clay loam (An)	41%, 84 ac	1%, 4ac			
Sycamore silty clay loam (Sr)	12%, 24 ac				
Sycamore silty clay loam, saline (St)	14%, 28 ac				
Valdez silty clay loam (Vc)					23%, 27 ac
Yolo silty clay loam (Ys)	4%, 9 ac				
Pescadero clay loam (Pc)	3%, 6 ac				
Reyes silty clay (Re)			38%, 72 ac	64%, 96 ac	31%, 36 ac
Tamba mucky clay (Ta)		15%, 41 ac	35%, 65 ac		
Suisun peaty muck (Sp)	3%, 7 ac	79%, 223 ac			
Joice muck (Ja)			27%, 51 ac	32%, 48 ac	43%, 49 ac
Water (W)	23%, 48 ac	5%, 13 ac		4%, 6 ac	3%, 3 ac
Surface water salinity (ppt)**					
Mean	2.60	N = 3.16; S = 3.90	NA	NA	NA
SD	2.43	N = 1.68; S = 1.98	NA	NA	NA

Notes:
*112 shoot level = 5.5-6.0 ft NAVD88; 123 shoot level = 4.0-4.5 ft NAVD88
** N = northern (Peytonia) side of club 123; S = southern (Boynton) side of club 123



Updated: 12/14/09

N W E S

1: 12,000 (1" = 1,000' at letter layout)

0 1,000 2,000 Feet

0 300 600 Meters

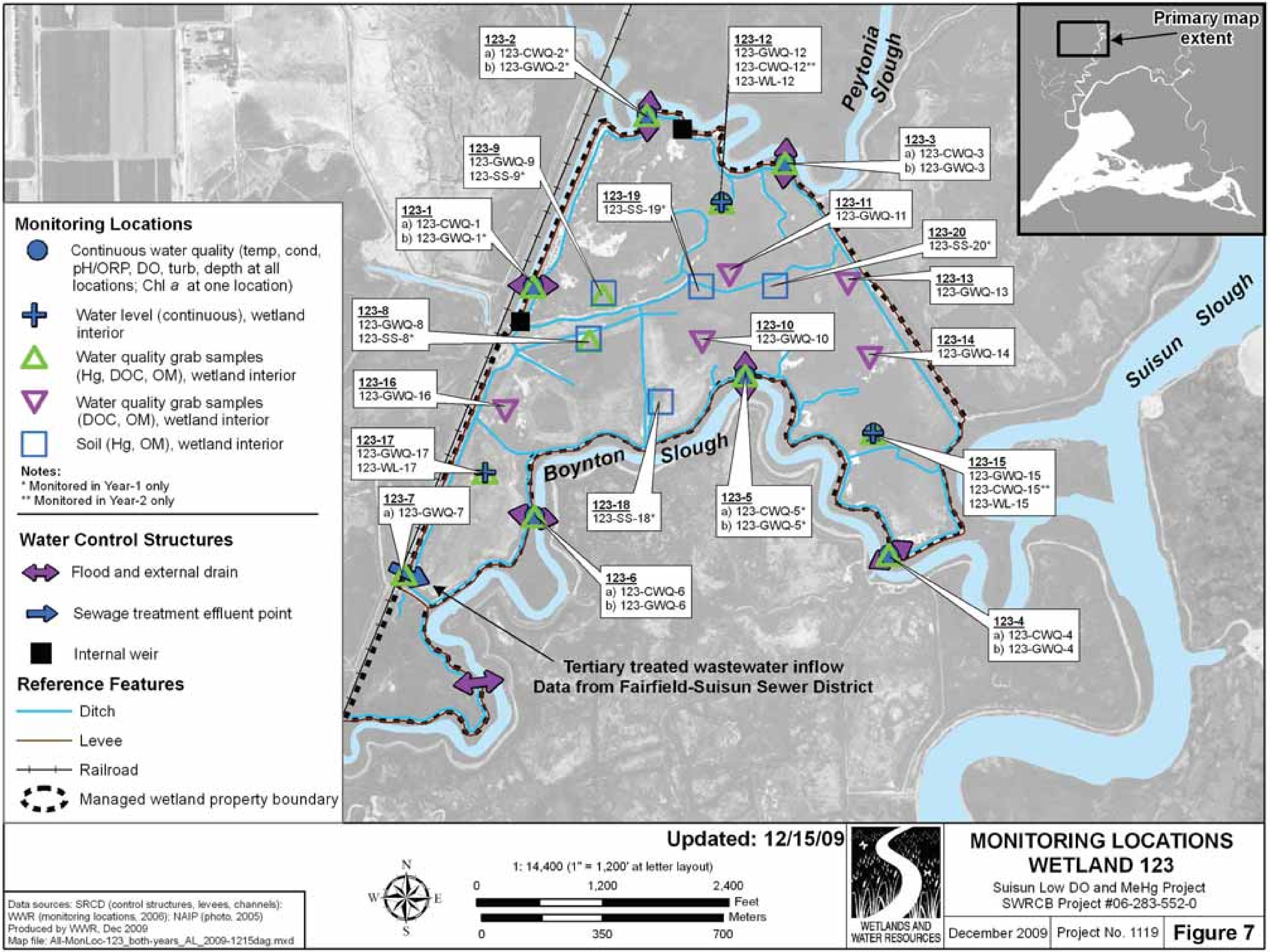
Data sources: SRCD (control structures, levees, channels); WWR (monitoring locations, 2006); NAIP (photo, 2005)
Produced by WWR, Dec 2009
Map file: All-MonLoc-112_both-years_AL_2009-1215dag.mxd

WETLANDS AND WATER RESOURCES

MONITORING LOCATIONS WETLAND 112

Suisun Low DO and MeHg Project
SWRCB Project #06-283-552-0

December 2009 | Project No. 1119 | **Figure 6**

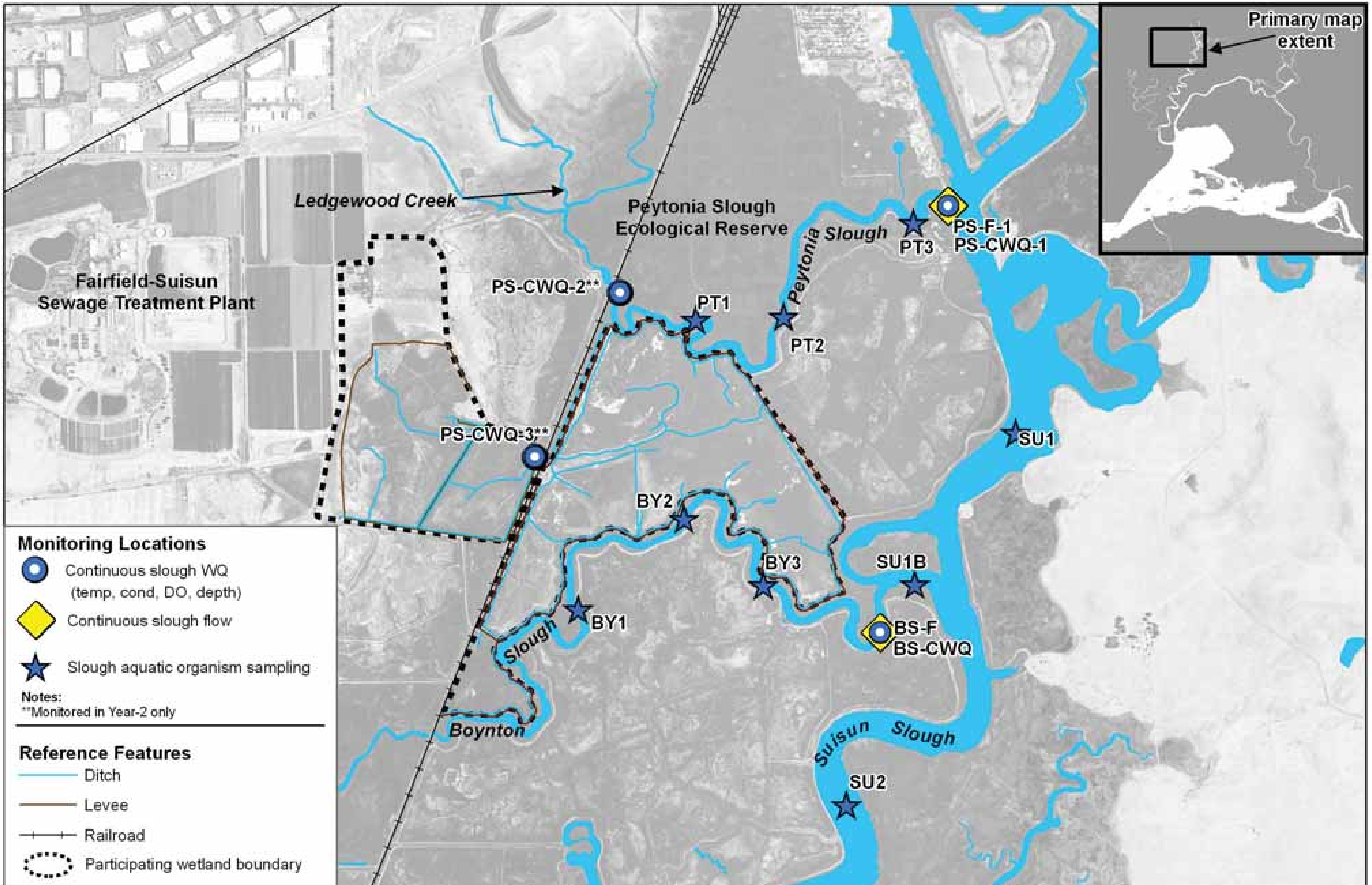


Data sources: SRCD (control structures, levees, channels); WWR (monitoring locations, 2006); NAIP (photo, 2005)
Produced by WWR, Dec 2009
Map file: All-MonLoc-123_both-years_AL_2009-1215dag.mxd

MONITORING LOCATIONS WETLAND 123

Suisun Low DO and MeHg Project
SWRCB Project #06-283-552-0

December 2009 | Project No. 1119 | **Figure 7**



Map updated: 12/16/09

1: 24,000 (1" = 2,000' at letter layout)

N W E S

0 2,000 4,000 Feet

0 600 1,200 Meters

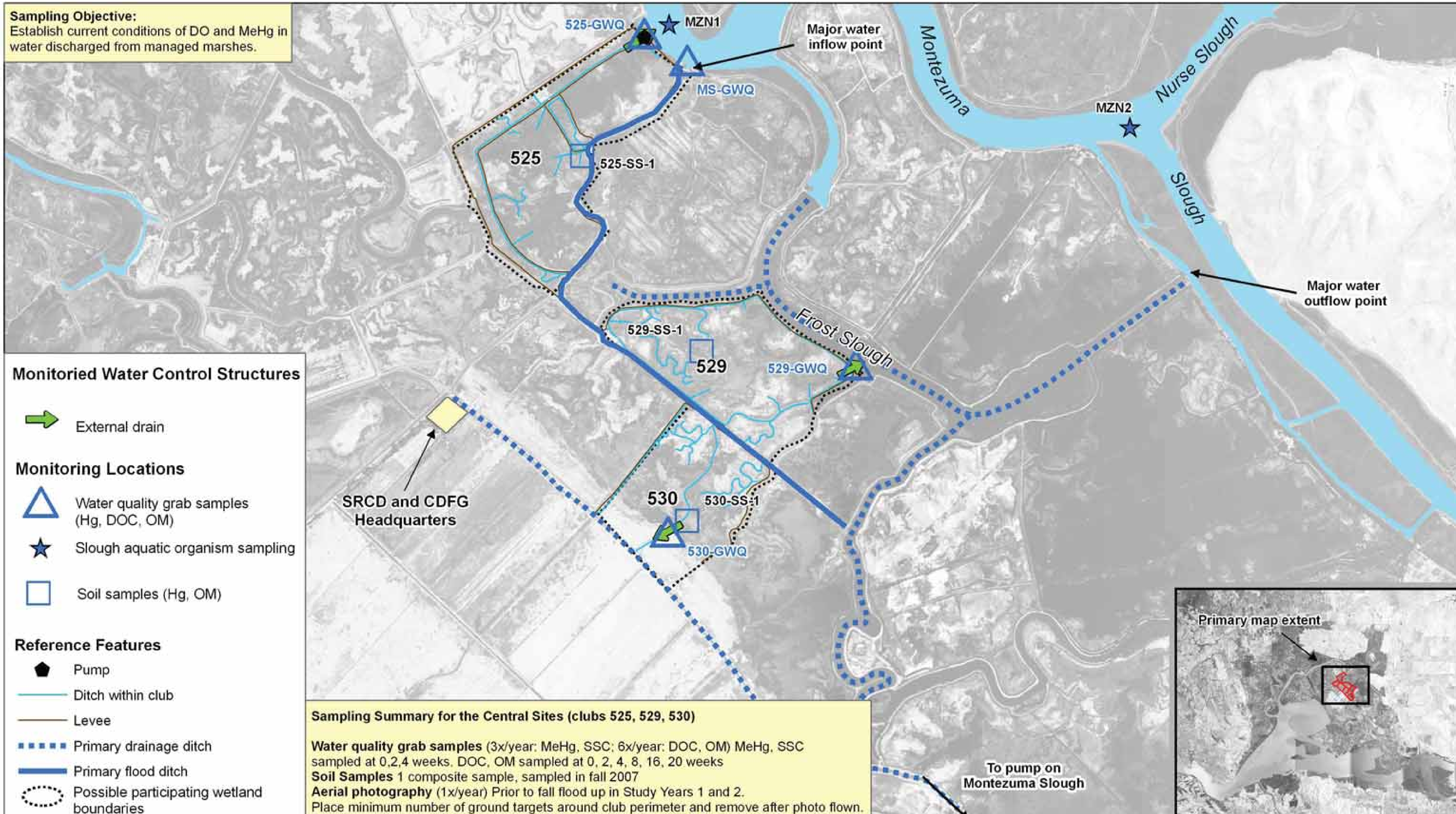
Data sources: SRCD (control structures, levees, channels); WWR (monitoring locations, 2006); NAIP (photo, 2005)
Produced by WWR, Dec 2009
Map file: external-mon-loc-NW_AL_2009-1216lee.mxd

WETLANDS AND WATER RESOURCES

EXTERNAL MONITORING LOCATIONS WETLANDS 112 AND 123

Suisun Low DO and MeHg Project
SWRCB Project #06-283-552-0

December 2009	Project No. 1119	**Figure 8**



Data sources: SRCD (control structures, ditches, levees);
WWR (monitoring locations, 2006);
NAIP (photo, 2005)
Produced by WWR, Oct 2007
GIS/Cartography by Dan Gillenwater
Map file: MonLoc-Central-Clubs_1119_2007_1008dg.mxd

WETLANDS AND WATER RESOURCES

MONITORING AND SAMPLING LOCATIONS CENTRAL WETLAND CLUSTER PROPERTIES 525, 529, 530

Suisun Low DO and MeHg Project
SWRCB Project #06-283-552-0

October 2007	Project No. 1119	**Figure 9**

1.3.2 Study Year 2 Sampling (Fall 2008)

In Year 2, we modified the sampling design from that in Year 1 based on the findings of the Year 1 monitoring period. The data collection period in Year 2 spanned from September 2008 to November 2008 to focus on the fall flood-up period, which is the period when low DO conditions are most prevalent.

The primary differences in the sampling design from the prior year were (1) to increase grab water quality sample frequency during the initial flood-up period, (2) reduce grab water quality sampling after the flood-up period, (3) reduce the number of samples collected at the water control structures to allow greater focus on wetland interior, (4) shift around the continuous water quality sampling to have more tidal slough stations, fewer stations at the water control structures and add internal stations, and (5) eliminate sampling at the three wetlands in the center of Suisun Marsh. These changes maintained the planned level of effort while refocusing that effort where we expected to gain the greatest knowledge.

1.4 Management Activities in Wetland Study Sites Years 1 and 2

Landowners in Suisun Marsh actively manage the vegetation community in their wetlands to achieve a beneficial food source for wetland dependant wildlife, manage for nuisance invasive vegetation, and reduce potential impacts to water quality. Management activities include both mechanical vegetation manipulation and water management techniques. Many of the vegetation management procedures are recommended by the SRCD to reduce the current low DO problems in Suisun Marsh and are outlined in "A Guide to Waterfowl Habitat Management in the Suisun Marsh" (Rollins, 1981), produced by CDFG. The management actions in Wetlands 112 and 123 for Year 1 and Year 2 are described below. A more complete discussion of management rationale and a description of management actions in the central wetland cluster can be found in Appendix A.

1.4.1 Wetland 112

In Year 1, Wetland 112 used both mechanical and water management techniques to control the vegetation community in the wetland.

Mechanical

- 80 acres were mowed using a standard rotary deck mower to reduce the amount of vegetative material available for decomposition.
- 25-acres of invasive cocklebur *Xanthium spp.* was sprayed when the managed wetlands were dry with herbicides to reduce the extent of this species

Water Management

In February of 2007, following the close of waterfowl hunting season, the water managers drained the marsh plain of the wetland and then performed a series of three flood-drain cycles to leach salts from the soils. After the last leach, the water level was held at half of the normal (fall management level) height until April 15, when the entire wetland was drained. The water managers then performed two flood-drain irrigations per month in May and June after which point the wetland was drained for the remainder of the summer. On September 28 water was brought to slightly below fall management level, then immediately drained and re-flooded to a desired height for fall management season. Once flooded to desired height the water was circulated at the highest rate possible. For detailed water control structure height see Water Control Structure log book for 2007/2008.

In Year-2, mowing was done with a flail mower instead of a rotary mower and vector control spraying treatment was completed. Aside from this change all other management activities were identical to those in Year-1.

1.4.2 Wetland 123

In 2007 Wetland 123 also used both mechanical and water management techniques to manage the vegetation community in the wetland.

Mechanical

- 5 acres of the wetland were mowed using a standard rotary mower in August to reduce the amount of vegetative material available for decomposition.
- 60 acres of the wetland were disked in August to reduce the presence of broad-leafed vegetation
- 125-acres of invasive cocklebur was sprayed with herbicides when the managed wetlands were dry to reduce the numbers of these species

Water Management

In February of 2007, following the close of waterfowl hunting season, the water managers drained the marsh plain of the wetland and then performed a series of three flood-drain cycles to leach salts from the soils. After the last leach, the water level held at half of the normal (fall management level) height until April 15, when the entire wetland was drained for the remainder of the summer. On September 15, 2007, water was brought to fall level or slightly below then immediately drained and re-flooded to a desired height for fall management season. Once flooded to desired height the water was circulated at the highest rate possible. For detailed water control structure height see Water Control Structure log book for 2007/2008.

In Year 2 the following changes to management practices were made:

1) A flail mower was used as opposed to a rotary mower
2) 120 ac of invasive cocklebur and pepperweed were treated with herbicides
3) The pre-flood period in September 2008 was followed by a 6-day drying period prior to full flood-up
4) Focused grading of the marsh plain to improve circulation and facilitate wetland drainage was performed in the southwestern corner of the main basin (near WCS 6)
5) Spray treatment of the ponds for the abatement of mosquitoes

All other management activities remained the same.

2 Integrated Findings on Key Study Questions

The original project grant proposal posed a number of key questions aimed at discerning the underlying processes leading to low DO and elevated MeHg events in the sloughs and the resulting ecosystem responses. This chapter addresses each of these questions using the data from this study and supporting information. We have re-organized and re-worded these original questions to present the findings of our study in a more complete and organized fashion. More detailed analyses from which these answers are based are contained in the seven technical appendices to this report.

2.1 Hydrologic Characteristics of Peytonia and Boynton Sloughs

The information in this Section is summarized from the Hydrodynamic Transport manuscript (Appendix **G**). Velocity and multi-parameter scalar sensors were deployed near the mouths of Boynton and Peytonia Sloughs in Suisun Marsh. The more than one-year deployment with a 15-minute sampling interval allowed analysis of tidal to seasonal hydrodynamics and transport characteristics of these two sloughs. Results show how tidal flows and scalar transport are modified by managed wetlands operations and the influence of climate and conditions in the watershed and in the larger Suisun region.

Peytonia and Boynton Sloughs have comparable size, drainage area, and tidal flow. The tidal flow velocity, reaching the 1 foot-per-second (fps) range each tide, is fast enough to almost fully evacuate the entire slough system each ebb tide. Indeed, the tidal range is more than half the depth in both sloughs. In absence of conflicting transport processes, we would expect these sloughs generally to support dispersive flux of material downstream because of ebb tide dominance, readily delivering materials like sediment and DOC from managed wetlands to Suisun Slough where they can mix with the regional area. The efficiency of this mixing varies throughout the year due to several periodic and oscillating processes.

Boynton Slough tidal flows range between about -800 (upstream flow) and +1200 (downstream flow) cfs while Peytonia Slough tidal flows range between about -700 and +800 cfs. Both sloughs exhibit an ebb-dominant tidal flow pattern typical of modified sloughs as the largest magnitude tidal flows occur during full moons on ebb tides. Peak ebb flows on Peytonia Slough reach approximately 1400 cfs, peak ebb flows on Boynton Slough reach approximately 1500 cfs. **Figure 10** shows only net flows for both sloughs to highlight the seasonal pattern. Net flows are determined using a low-pass filter to remove oscillations at the tidal timescale. Variability in the **Figure 10** signals is therefore due to climate, inflows, evaporation, and the lunar cycle.

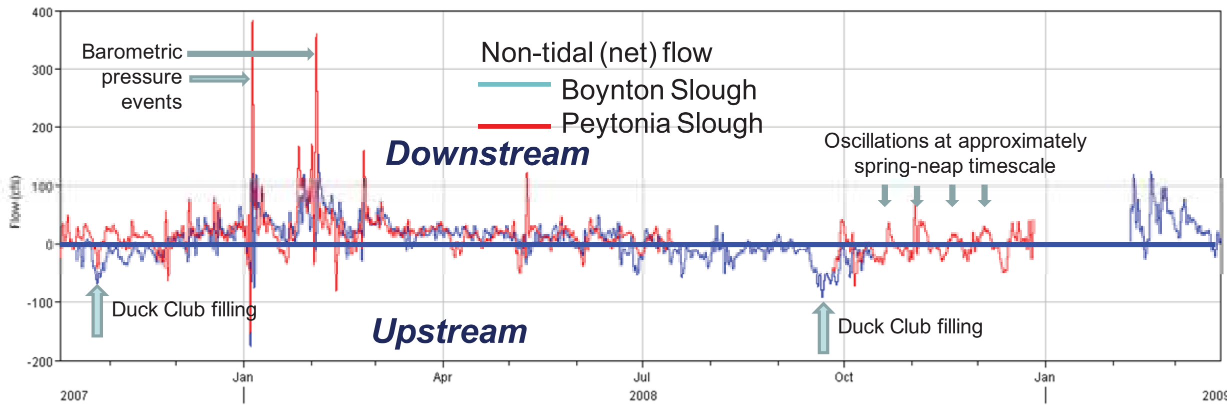


Figure 10. Digital low-pass filter of tidal flow time series- September 2007 – March 2009

Both sites exhibit generally positive outflow flux (dispersive mixing) in the winter months and negative outflow flux (trapping) in the summer and fall months. Winter positive outflows in Peytonia Slough are due to watershed outflows during winter storms and in Boynton Slough are due to fairly minor rainfall-runoff (it has a very small drainage area) combined with larger spring tides. Summer negative outflows are likely due to evapotranspiration from the tidal marshlands located at the head of Boynton Slough and along the northern side of Peytonia Slough (see **Figure 4**). These tidal marshlands also likely contribute some evapotranspiration-driven net upstream flow during the fall as well, at least until the vegetation reaches the end of its growing season. The magnitude of upstream flow increases during the fall months when managed wetlands are flooded in advance of the fall hunting season. Since most managed wetlands along Peytonia and Boynton Sloughs are dry during the summer, water is needed at flood-up not only to flood the wetlands, but also to saturate the soils (see Section 3.7, below). For example, Boynton Slough exhibits strong upstream net flow beginning in late September 2007 and 2008 when managed wetlands begin filling. Upstream net flow in Boynton Slough ramped up to around 70 cfs by September 21, 2008 and maintained this level of upstream net flow until around September 28, 2008.

There is a clear spring-neap tide oscillation evident in the filtered flow signal that can reach nearly 50 cfs, about 10% of the tidal magnitude (**Figure 11**). Net flow on both sloughs oscillates approximately with lunar maximums. Both sloughs generally fill at a peak rate of 10-40 cfs around full and new moons, and drain similar volumes during lunar quarters. **Figure 11** also includes barometric pressure that also exerts influence on net flow. Observed net flow is a superposition of uncorrelated lunar and barometric pressure forcing along with the seasonal timescale oscillations.

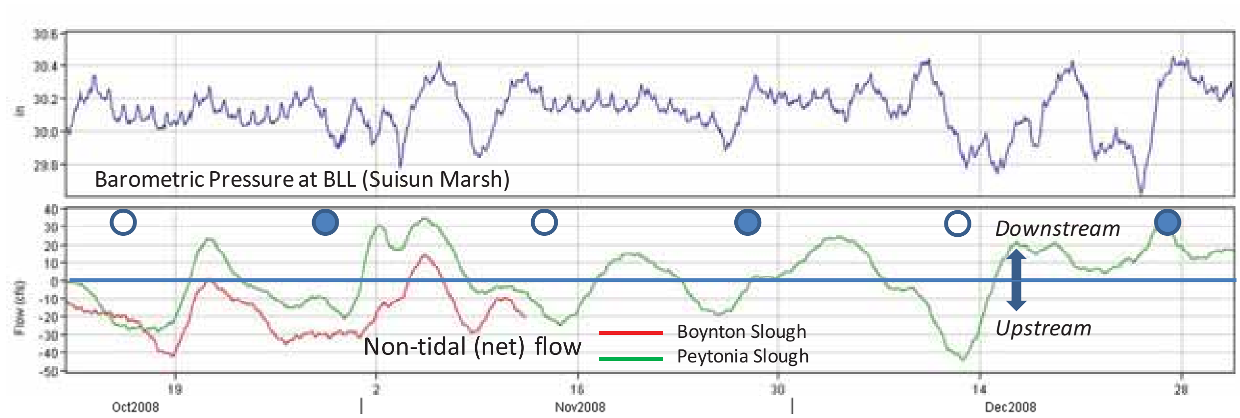


Figure 11. Influence of Lunar Phase and Barometric Pressure on Net Flow

Water flux in both sloughs can be briefly but significantly affected by low barometric pressure events associated with storms. **Figure 12** shows a low pressure event on January 4, 2008 when both sloughs responded first by rapidly filling. Flood tide flows spiked up to 1,000 to 1,200 cfs. Peytonia Slough flood flow spiked more than Boynton despite its slightly smaller size. This is likely due to the existence of tidal marsh in the Peytonia Slough watershed. The ensuing ebb tide exhibited drain flows about two times the volume of previous ebb tides.

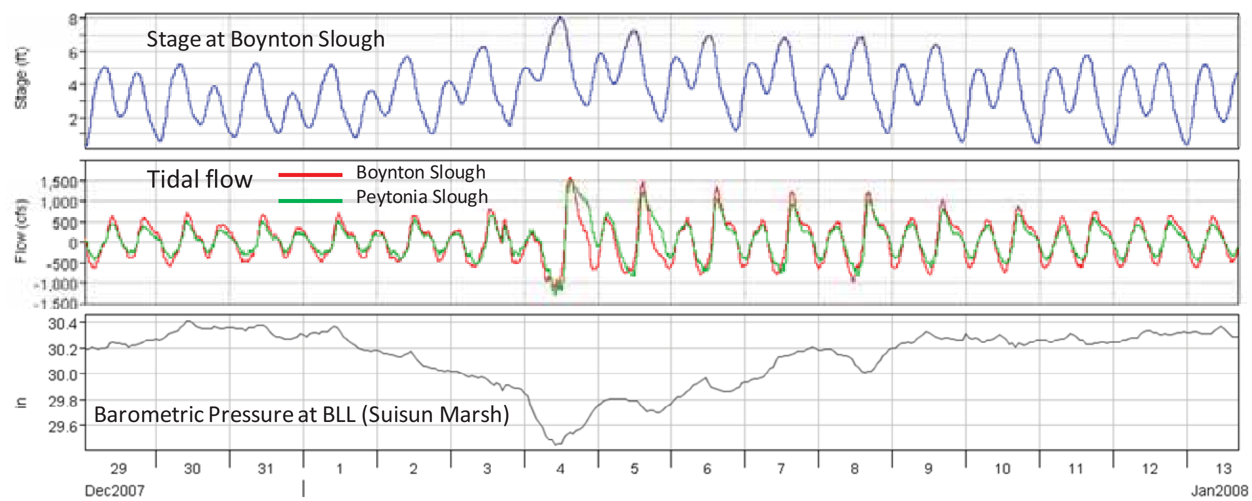


Figure 12. Tidal Flow Response to Low Pressure Event

2.2 Quality of Water Supplied to the Managed Wetlands

The information in this Section is summarized from the Water Quality manuscript (Appendix **C**) and the Hydrodynamic Transport Manuscript (Appendix **G**). The managed wetlands studied in this project have three major sources of water, which are presented in their relative orders of importance: tidal water from adjacent sloughs which can include watershed outflows, effluent from the FSSD treatment plant, and direct rainfall. The water quality of each of these sources is described individually below.

2.2.1 Tidal Sloughs

Tidal water into Peytonia and Boynton sloughs originates from Suisun Slough. This source of water is the largest supply to the wetlands. It is used to flood the wetlands in the fall and winter and for much of the remainder of the year, it is used to support maintenance flows. Peytonia Slough is connected to the watershed of Ledgewood Creek and a large portion of the stormwater runoff for the western part of Fairfield (**Figure 4**). Boynton Slough has little if any watershed inputs.

Figure 13 presents the DO concentrations in Peytonia and Boynton Sloughs as measured over the course of this field study. The water quality standard for DO concentration (7 mg/L) is shown in the figure and the dates identify when the sloughs were above and below the standard. DO levels within the sloughs exhibited a clear seasonal variation. Just prior to fall managed wetland flood-up in September of both years, both sloughs had DO concentrations generally between 6 and 8 mg/l. This water is used for the initial managed wetland flood cycles. Following the initial flood cycles, slough DO levels are influenced by managed wetland operations (discharge and net upstream flow) and seasonal variations (discussed in Section 3.8, below). During the study period, DO concentrations were below the water quality standard from mid September through mid December. After that time, DO concentrations were generally above the water quality standard until mid April, at which point they dipped below the water quality standard until late summer 2008. The impact of managed wetlands operations and seasonal climatic factors upon slough water quality are described in detail in Section 3.8. The summer 2008 low DO levels when the diked managed wetlands were mostly dry may be due to higher summer water temperatures (lower saturation concentration), phytoplankton productivity and decomposition in the sloughs, and tidal wetlands along each slough both promoting slight net upstream flows and draining organic carbon into the sloughs with the ebb tide. In other words, summer low DO levels in sloughs influenced by tidal wetlands can drop under natural conditions.

Slough salinity levels also vary seasonally. **Figure 14** suggests there was an overall flux of salt upstream as an annual average. The annual flux is clearly driven by summer and fall conditions when salt is imported upstream with the net flow. Much is returned over the winter months but at a slower rate. There also appears to be a significant difference between Peytonia and Boynton on this issue. Boynton, which is dominated by managed wetland operations, fluxes much more water and salt upstream in summer/fall. Peytonia is more or less balanced though the fall 2008 period showed slightly more tendency to flux salt upstream.

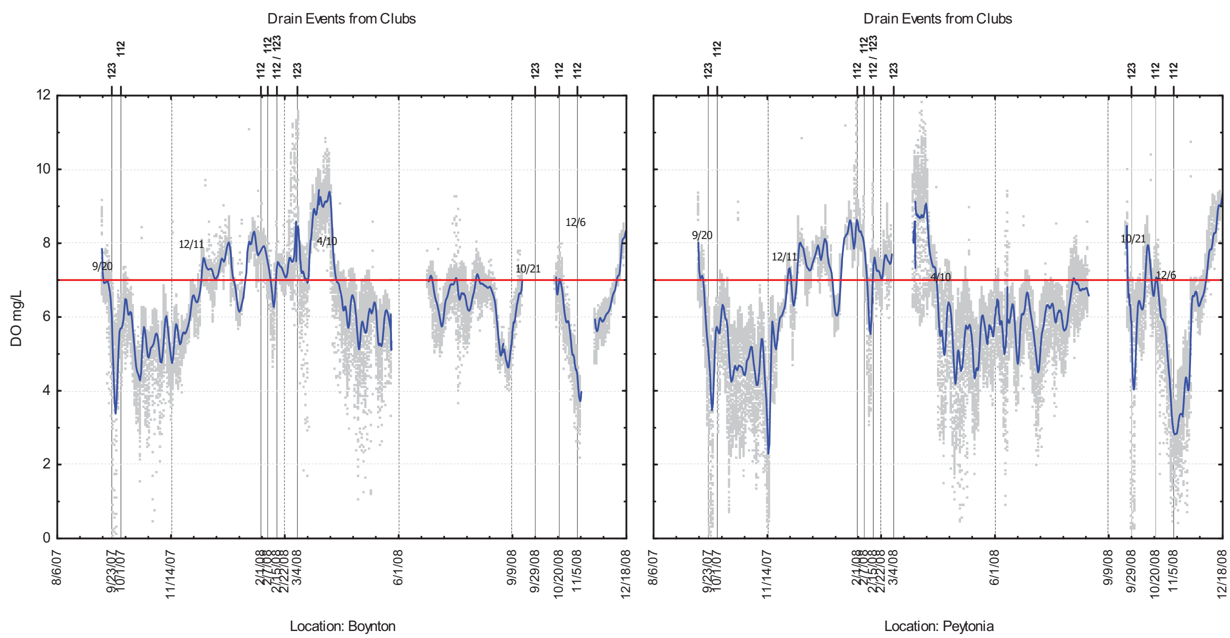


Figure 13. DO Concentration Time Series in Peytonia and Boynton Sloughs

DO data shown is 15-minute data. Top axis gridline (black) identifies when a drainage event occurs from a wetland and the axis labels the wetland from which the event occurred. DO water quality standard is 7 mg/L and is identified with the red line. Dates on graph shows when the blue fitted DO line (negatively weighted exponential fit) crosses above or below the water quality standard.

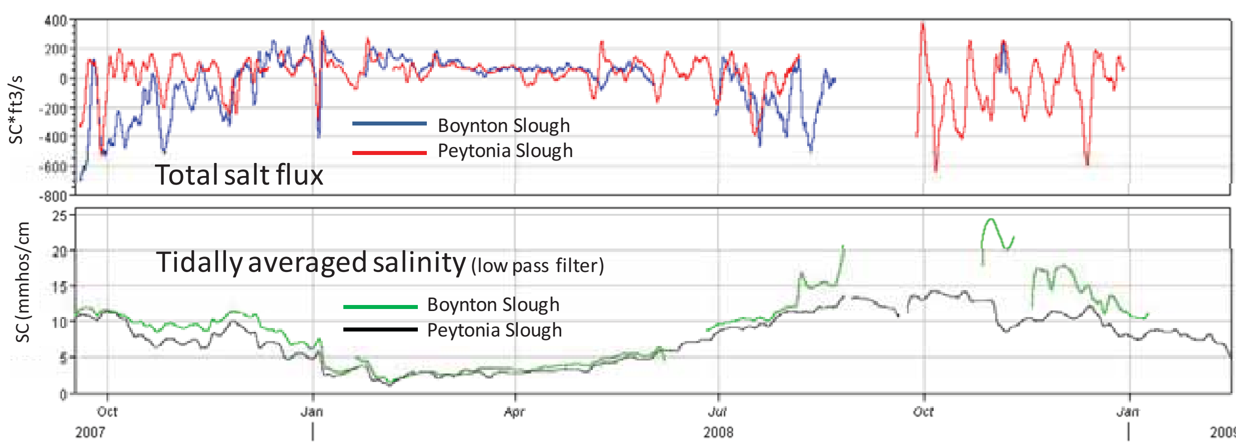


Figure 14. Total Salt Flux and Tidally Averaged Salinity for Peytonia and Boynton Sloughs

No direct measurements of DOC or MeHg were made within Peytonia or Boynton sloughs.

2.2.2 Fairfield-Suisun Sewer District Treatment Plant Effluent

The FSSD treatment plant treats an average of 16 million gallons per day (MGD). Approximately 90% of the FSSD discharge goes directly to Boynton Slough, with a portion of that water being used seasonally to flood three managed wetlands (Wetlands 112, 122, and 123; see **Figure 4**). The remaining approximately 10% is used for landscape irrigation (FSSD 2010). In the fall during this study, approximately 13% of the FSSD tertiary treated wastewater was discharged to Wetland 112 while the historical annual average of that discharge was approximately 5% of FSSD wastewater. There is no meter on the outflow to Wetland 123, so no estimate for the relative contribution of FSSD effluent is available for this location.

The quality of this discharged water is relatively good: DO is relatively high and mercury, DOC, and BOD levels are low. The FSSD tertiary treated water has discharge requirements for DO. Monthly DO averages in the fall (when the sloughs are most apt to have depressed DO levels) are in the range of 6 – 7 mg/L. Organic carbon, SUVA and MeHg were not directly measured from the FSSD discharge flows. However, those constituents were measured at the outfall location into the wetland (**Figure 6**). Water sampled from those locations had the lowest median DOC values (7 mg/L), filtered MeHg (0.1 ng/L), and unfiltered MeHg (0.2 ng/L) for all the stations that were monitored at both managed wetlands.

2.2.3 Rainfall

No water quality data were collected on rainfall. Hydrologic data presented in Appendix **B** suggest direct rainfall into the managed wetlands was relatively negligible with regards to the key concerns being addressed by this study.

2.2.4 Watershed Outflows

This study did not sample water quality entering Peytonia Slough through Ledgewood Creek or the large stormwater outfall draining much of western Fairfield (**Figure 4**). Ledgewood Creek drains a large watershed consisting of several thousand acres of irrigated annual and perennial crops, portions of urban western Fairfield, and natural communities of the coast range north of Fairfield (**Figure 3**). Stormwater enters Suisun Marsh untreated. These flows may contain a range of water quality constituents consistent with these land uses, including oil and grease from roadways, nutrient-enriched agricultural and urban irrigation runoff, and possibly herbicides and pesticides and the like.

2.3 Water Quality within the Managed Wetlands

The information in this Section is summarized from the manuscripts on Water Quality (Appendix **C**), Organic Matter (Appendix **F**), and Mercury (Appendix **E**). The high resolution continuous and discrete water quality data from within Wetlands 112 and 123 reveal several generalities with regard to major parameters of interest. These generalities are discussed below.

2.3.1 Dissolved Oxygen

DO levels were monitored with remotely deployed instruments at 15-minute intervals during the field sampling periods. Most sample stations were located at the wetland discharge location inside the managed wetland; some stations were located in ponds within the wetland interiors. DO was also measured at the mouths of Peytonia and Boynton Sloughs. **Figure 15** displays DO concentrations and water level at a representative perimeter monitoring station at Wetland 123. Dissolved oxygen concentrations at perimeter monitoring stations within the managed wetlands dropped to near 0 mg/L during the fall drain events in both study years when water elevations are dropped in the managed wetlands to at or below marsh level. During fall discharge, DO concentrations were continuously near or at 0 mg/L at several discharge locations for about 3 – 5 days at Wetland 123 and for about 5 – 15 days at Wetland 112. After the drain events, DO at the wetland discharge locations remained depressed below the 7mg/l DO standard into November and December. DO concentrations dropped to near 0 mg/L but these drops were short-lived and part of a diurnal cycle which typically saw DO vary by about 3 – 5 mg/L during tidal events. DO trends at interior wetland monitoring stations showed sustained periods of near 0 mg/L throughout the fall period.

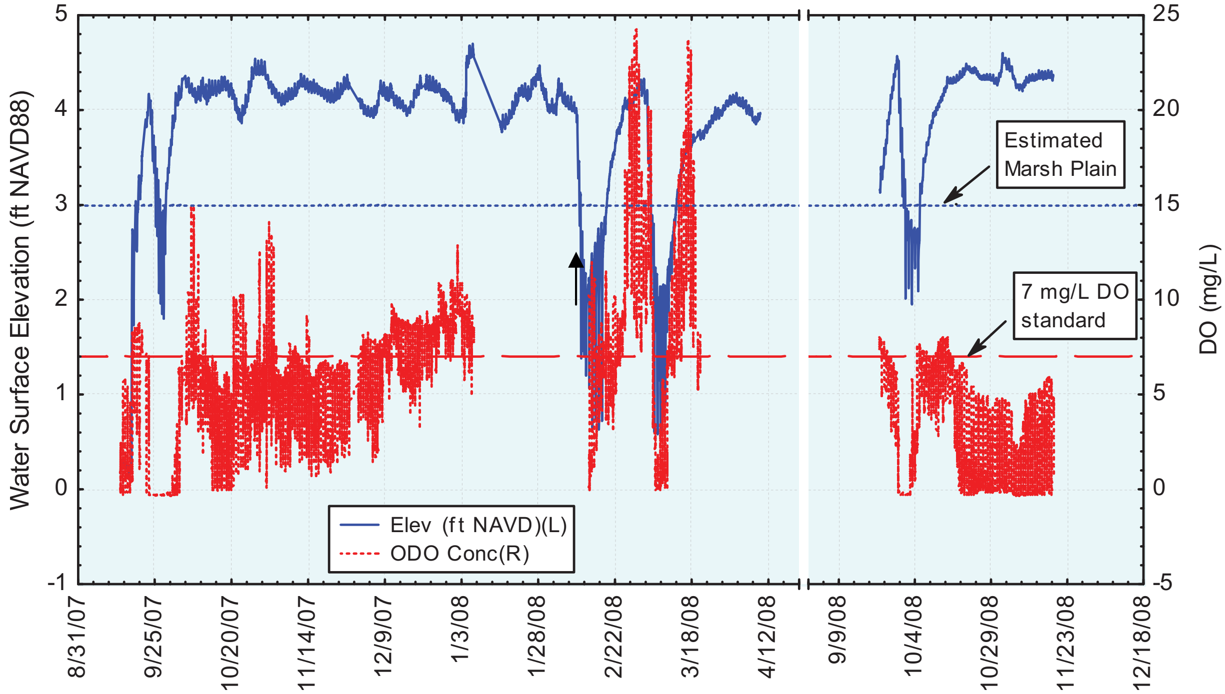


Figure 15. DO and Stage at Representative Perimeter Station, Wetland 123

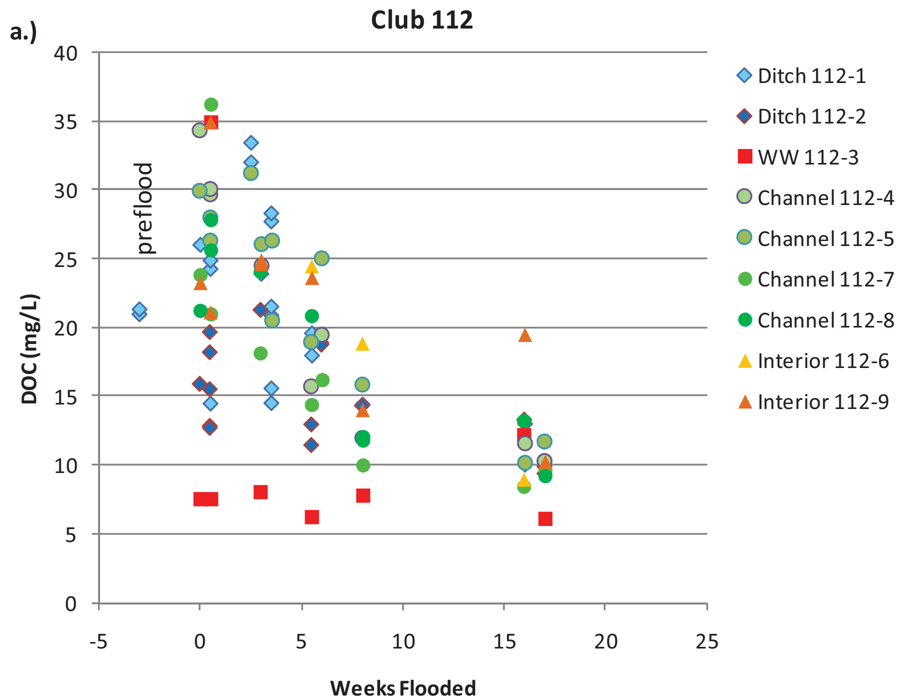
Note the time gap between April and September 2008; wetland water quality data were not collected during the spring-summer 2008 dry period in the wetland management annual cycle. Data from Station 123-4 on Boynton Slough side of wetland.

During spring drawdown periods, perimeter wetland station DO concentrations were depressed below the levels that occurred during standard flow maintenance conditions. DO concentrations dropped to near or at 0 mg/L during these spring drain events. However, periods of extended DO near 0 mg/L were much shorter when compared to the fall. Diurnal cycles tend to pull DO concentrations up during this period with DO levels typically varying by 5 mg/L during each cycle.

2.3.2 Dissolved Organic Carbon

DOC levels were laboratory measured with discrete field grab samples collected at wetland discharges, wetland interior ponds and channels, and in Montezuma Slough at the Frost Slough intake. For the period during which comparable data was collected (October 2007 – January 2008), DOC concentrations were similar between Wetlands 112 and 123 as well as with Wetlands 525, 529 and 530. DOC concentrations within these wetlands were also higher than found in Montezuma Slough. From October through December, DOC concentrations in the wetlands were typically 2.5 – 7X higher than found in Montezuma Slough.

DOC concentrations varied widely from 3 to 100 mg/L, with the highest DOC concentrations measured during drawdown in Wetland 123 in September 2008 (**Figure 16**). Soils in Wetland 123 are Suisun Peaty Muck which are high in organic matter. DOC concentrations, particularly in Wetland 112, were higher during the earlier weeks after flooding, dropped over time and seemed to stabilize after approximately 5 weeks of flooding. Within both wetlands, sites representing waste water inflows (112-3, 123-6 and 123-7) had significantly lower DOC concentrations compared to other sites. No clear differences were found in DOC concentration between interior channel and interior marsh plain sites; however, the perimeter (ditch) sites had lower concentrations than the interior sites. Taking into account time since flood-up and landscape position, there were no statistical differences in DOC concentration between wetlands or vegetation management setting.



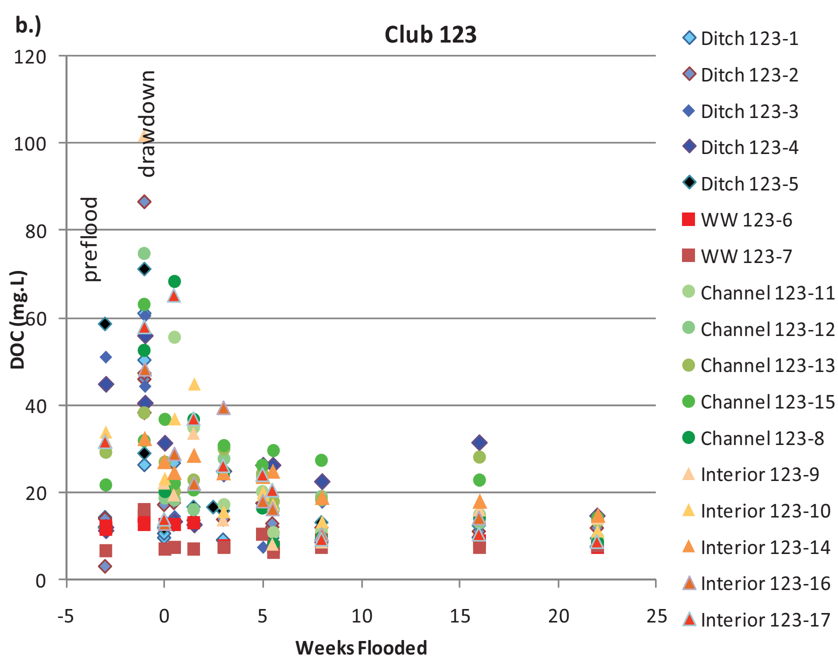


Figure 16. DOC Levels in Samples from (a) Wetland 112 and (b) Wetland 123

2.3.3 Methylmercury

Methylmercury concentrations in grab water samples from both Wetlands 112 and 123 followed essentially the same patterns as DOC. Methylmercury levels are generally high following initial fall flood-up of the wetlands then taper off to lower levels approximately two months later. **Figure 17**, which displays MeHg levels in Wetland 112 in Year-1 of the study, illustrates this trend. The lowest MeHg levels were found at sample sites near the FSSD sewage effluent discharge points. In Wetland 112, sample location 112-GWQ-3 is located near the FSSD outfall location (**Figure 17**). During initial flood-up, MeHg levels are negatively correlated with DO levels.

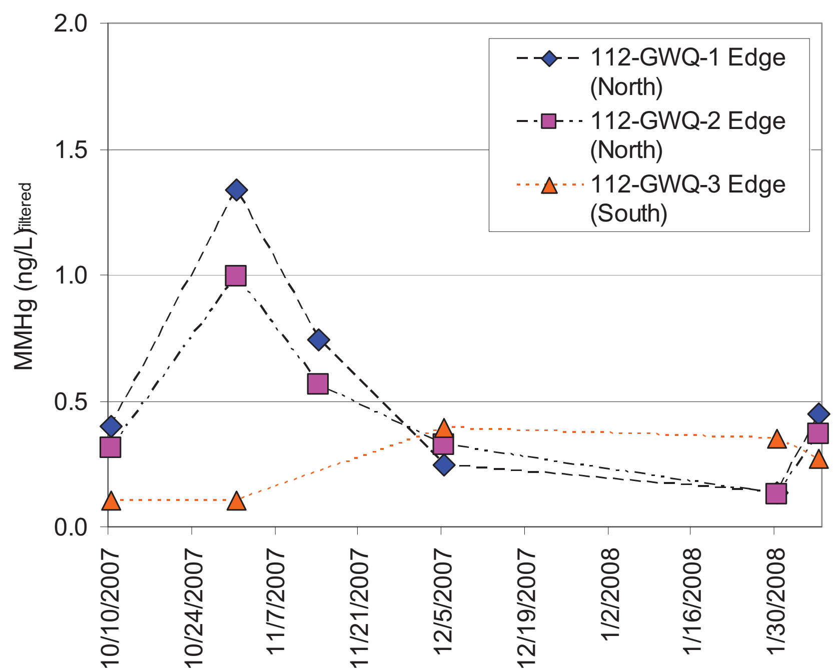


Figure 17. Year-1 MeHg Concentrations at Perimeter Sample Locations, Wetland 112

For this dataset, DOC concentrations correlations with MeHg concentrations were statistically significant (p=0.0000) at the perimeter stations and predicted about 50 – 60% of the variance. For the interior stations, the correlations between DOC and MeHg were not as strong, predicting about 30 – 36% of the variance. DO concentrations had a visible effect on mercury values. When DO concentrations for the discrete samples were > 4 mg/L at the perimeter sites, MeHg was typically below 0.2 ng/L (DO concentrations within the discrete samples taken from the perimeter sites were either <0.5 or > 4 mg/L). For the interior stations, DO concentrations > 4 mg/L typically had filtered MeHg concentrations < 1 ng/L and unfiltered MeHg concentrations

≤ 2 ng/L. Below DO levels of about 3 mg/L, both unfiltered and filtered MeHg increased dramatically. About one half the total MeHg was in dissolved form.

2.3.4 Salinity

Salinity levels were monitored with remotely deployed instruments at 15-minute intervals during the field sampling periods. Most sample stations were located at the wetland discharge location inside the managed wetland; some stations were located in ponds within the wetland interiors. Salinity was also measured at the mouths of Peytonia and Boynton sloughs.
Initial water column salinity within the wetlands in the fall is about 8 – 10 ppt. Fall flushes do not seem to reduce salinity greatly, though water column salinity does decrease through the fall. Late winter flushing clearly removes salts from the soils. With each winter flush event, water column salinity levels spike (Appendix **C**). Two flushing events at Wetland 123 and three flushing events at Wetland 112 each result in a large salinity spike in the water column as salinity is drawn from the soils into the water column. These spikes are very short lived with salinity returning to levels below 1 – 2 ppt upon raising wetland water back to management levels.

The data suggest salinity flushing (also known as a leach cycle) at Wetland 112, which is one of the few managed wetlands than receives water directly from the FSSD treatment plant, is more effective than at Wetland 123. By the third flushing event at Wetland 112 late in the first winter, water column salinity is much lower than the earlier events. Salinity levels in the fall reach a maximum of about 8 ppt. At Wetland 123, the last late winter flushing event has a peak similar to the first peak and salinity levels the following fall are near 10 ppt. The data suggest late winter flushing events can draw salts more effectively from the soils and lead to lower salinity levels in the wetland the following year, which suggests that increasing flushing events (especially via higher circulation rates) can be an effective strategy for managing soil salinity. Other factors may be affecting salinity levels and the data set is limited. See Appendix **C** for more detail.

2.3.5 Within-Wetland Spatial Variation in Water Quality Characteristics

Water quality spatial distribution within the wetlands differs between the wetlands and this appears to be due to their overall hydrology. At Wetland 123, water quality at the perimeter stations differed from the interior, with perimeter DOC and MeHg concentrations being lower than at the interior sites. Wetland 123 receives water directly from Boynton and Peytonia Sloughs. These differences suggest slower rates of water mixing within the wetland. At Wetland 112, water quality is more similar amongst all sites. Wetland 112 has fewer water inflow-outflow locations and receives a greater percentage of its inflow from FSSD discharges. It also had interior water circulation improvements constructed in 2007 just before this field study got underway. For both wetlands, the lowest DOC and MeHg values and the highest DO levels were at stations receiving effluent discharges.

2.3.6 Impacts of Summer Land Management on Water Quality Characteristics

The effects on water quality of land management efforts undertaken when the wetland is dry during the summer appear relatively short-lived. Land management work at the wetlands included mowing, discing and herbicide application. These wetlands had different water quality responses to land management. For Wetland 112, stations at which land management occurred had higher DOC and SUVA levels in the early fall flood-up periods.

Although the differences were not statistically significant, Wetland 123 had generally higher levels of DOC following fall flood up than did Wetland 112. This could be due to several factors. The soils of Wetland 123 are more organic than those in Wetland 112. Also, at Wetland 123, discing is used to control weeds and manage lands as compared to mowing and herbicides at Wetland 112. Discing causes greater disturbance than herbicide applications or mowing and could accelerate DOC diffusion through greater oxidation and greater infiltration into the upper soil layers. Thus, discing would be expected to increase DOC leaching from the soils.

2.4 Sources and Relative Contributions of Organic Matter Contributing to Biological Oxygen Demand

The information in this Section is summarized from Organic Matter manuscript (Appendix **F**). Biological oxygen demand – a measure of oxygen required for decomposition of organic matter and/or oxidation of inorganic materials such as sulfide – is introduced into many surface water catchments via sources of organic matter such as sewage effluent, surface runoff, and natural biotic processes (Hemond and Benoit 1988). In addition to the addition of labile DOC from wastewater inflows, low DO concentrations in the interior and channel sites during the drawdown and after rewetting point towards sources of labile organic matter in the water column from a mixture of (1) soil organic matter (i.e., wetland soils), (2) macrophytes (i.e., wetland plants), and (3) inflow waters (i.e., tides, FSSD, watershed).

Specific ultraviolet absorbance (SUVA) is the ratio of a sample's absorbance at 254 nanometers divided by its DOC concentration. SUVA is often used as a proxy for aromatic (humic compound) content (Weishaar et al. 2003). Bulk DOM from fresh plant and algal sources has lower aromatic content compared to more degraded DOM. The exponential shape of the absorbance curve – the spectral slope (*S*) – has been shown to relate to DOM aromatic content and molecular weight; decreasing *S* is associated with higher aromatic content and increasing molecular weight (Helms et al. 2008; Pellerin et al. 2009).

In the study, SUVA values generally indicate a spike in humic compounds (degraded DOM) during the initial fall flooding events with the highest values during the fall drain events. In Wetland 123, there was a notable increase in SUVA values after the first few weeks of flooding. This increase could indicate the consumption of more labile DOM and/or production of more highly processed DOM with higher aromatic content. In other words, the fall is characterized by decaying plant matter (left over from spring growth and summer wetland management activities). By March, week 22 following flood-up during the first year of sampling, SUVA values declined in Wetland 123, which may reflect the release of DOM with lower aromatic content from growing vegetation and/or algae, or may also reflect hydrologic flushing of wetland derived DOM and replacement with a new pool of DOM by inflow waters. The lowest *S* values were seen during drawdown in Wetland 123, which like the elevated SUVA values suggests release of higher molecular weight, aromatic DOM from degraded organic matter during that period.

The fluorescence index (FI) has been widely used to indicate relative contributions of algal versus terrestrial derived DOM; algal derived material which has lower aromatic content and lower molecular weight is associated with higher FI values, while more highly processed, terrestrial derived material that has greater aromatic content and higher molecular weight is associated with lower FI values (McKnight et al. 2001; Jaffe et al. 2008). FI values in this study ranged between 1.2 and 2.0, indicating there were significant changes in DOM composition and source among samples. Most notably, FI values were highest (more algal derived) in waste water influenced sites (~1.9), which is commonly reported (Hudson et al. 2007). The increase in FI values in Wetland 123 at week 22 (March 2008) supports the hypothesis there was significant contributions of DOM from algal production or leached from vegetation growing in the wetland. This shift could be due to production within the wetland, as well as due to the inflow and exchange of water from outside sources. The high FI values associated with site 123-1 indicates that this ditch location was influenced by either wetland-generated plant matter or FSSD inflows, including discharges from adjacent wetlands that can reach this intake location.

2.5 Availability of Labile Mercury in Soils for Methylation and Resulting Methylation Potential

The information here is summarized from the Mercury manuscript (Appendix **E**). Average total inorganic mercury (Hgt) concentrations of surface soils in the northern wetlands (Wetlands 112 and 123) were 0.097 ± 0.01 micrograms per gram dry weight (µg g^{-1} dw) compared to 0.148 ± 0.02 µg g^{-1} dw at the central wetlands (Wetlands 525, 529, 530). Average MeHg concentrations are similar at northern (1.835 ± 0.515 nanograms per gram dry weight [ng g^{-1} dw]) and central (4.374 ± 3.540 ng g^{-1} dw) wetland considering the large variability between sites and clubs. The ratio of MeHg to total Hg was used as a proxy for methylation potential (Gilmour et al. 1998; Heim et al. 2007; Kimball 2006; Krabbenhoft and Wiener 1999). In this approach, the assumption is that the larger the ratio, the greater the potential for methylation. The ratios in club soils ranged from 0.08 to 8.04 percent. The lowest value was observed in soil collected from depth at Club 530 and the highest value was from Wetland 525. A comparison of Wetland s 112 (percent MeHg/Hgt = 0.73 ± 0.207) and 123 (percent MeHg/Hgt = 2.42 ± 0.732) show similar potential for methylation given the uncertainties of the ratios. Soil collections as part of this project were generally used for screening and larger sample sizes would be needed to determine significant differences between the clubs.

Chemical evidence points at microbial degradation of DOC as possibly responsible for rapid depletion of DO, thus the shift to more aromatic structures. Concomitant decrease in DO concentration and increase in dissolved MeHg concentration resulting in release of DOC from sediments likely brought both inorganic Hg and MeHg into the water column.

2.6 Relationship between Dissolved Oxygen Sags, Site Vegetation (Biomass), and Methylmercury Production

The information in this Section is summarized from the Mercury manuscript (Appendix **E**). Dissolved oxygen appeared to be an important factor in predicting MeHg at perimeter sampling locations (**Figure 18**). When DO concentrations for the discrete water samples were > 4 mg/L at the perimeter sites, MeHg was typically below 0.2 ng/L (DO concentrations within the discrete samples taken from the perimeter sites were either <0.5 or > 4 mg/L). For the interior stations this trend is less clear (**Figure 18**). DO concentrations > 4 mg/L typically had filtered MeHg concentrations < 1 ng/L and unfiltered MeHg concentrations ≤ 2 ng/L. Below DO levels of about 3 mg/L, both unfiltered (dissolved and sediment-bound) and filtered (dissolved) MeHg increased dramatically. About one half the total MeHg was in dissolved form. Whether MeHg is in the dissolved or sediment-bound form affects the pathways through which it could enter the food web.

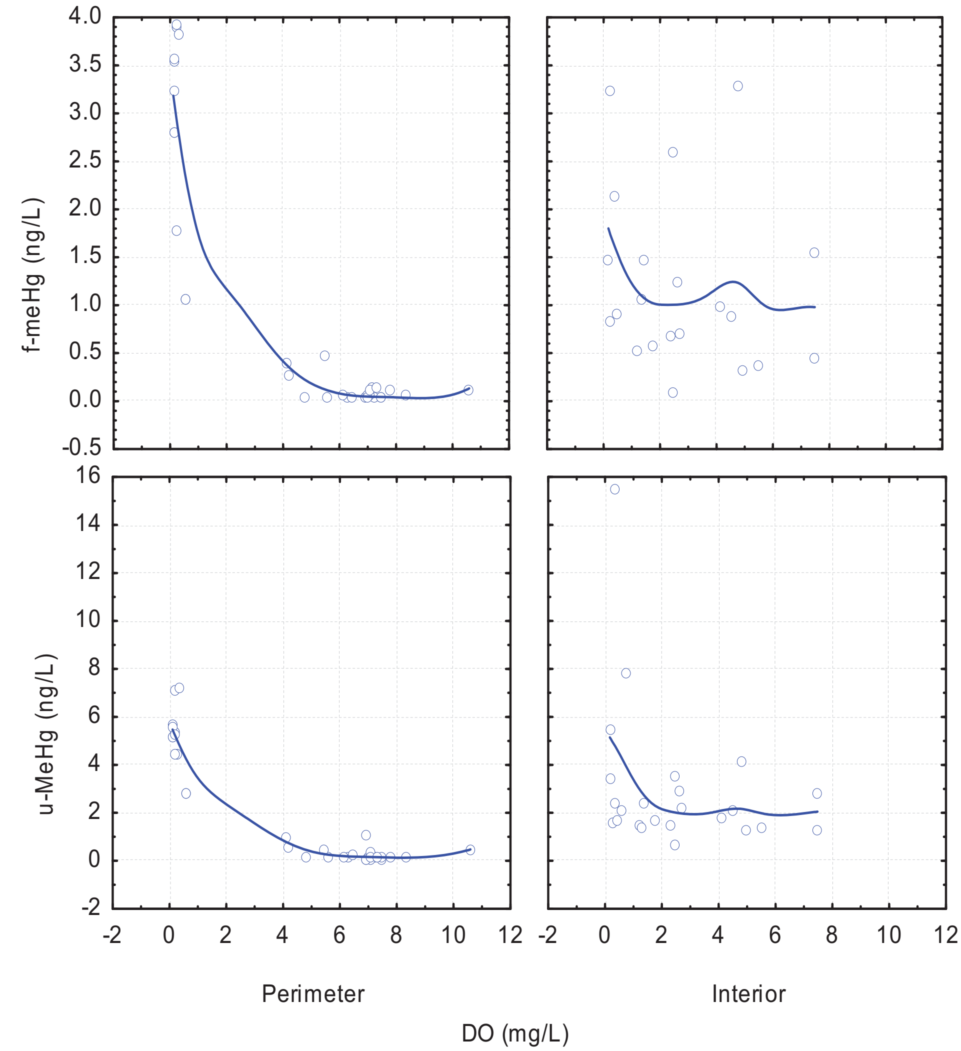


Figure 18. Relationship between MeHg Concentration and DO Level in Samples Collected in Wetlands 112 and 123

Laboratory studies using microcosms to investigate the relationships between vegetation, dissolved oxygen, and MeHg in pre-flooded and non-pre-flooded sediment treatments found higher MeHg concentrations in pre-flooded sediment plus plant treatments compared to sediment only treatments (**Figure 19**). Non-pre-flooded treatments of plant plus sediment also increased MeHg concentrations but more gradually over a longer period of time. There was a negative significant correlation ($r^2 = 0.74$, $p = 0.03$) between MeHg and oxygen in pre-flooded treatments of plant plus soil and soil only. Lower oxygen concentrations resulted in higher

MeHg concentrations. Microcosms which were pre-flooded resulted in higher MeHg concentrations in the presence of vegetation. Treatments without vegetation added did not show the same ability to produce MeHg regardless of pre-flooding. Oxygen concentrations are a factor influencing MeHg production in pre-flooded treatments. Additional laboratory studies were conducted to investigate the relationship between varying plant material and sediment under aerated and non-aerated conditions. For any given treatment of vegetation addition the non-aerated samples resulted in a higher concentration of MeHg. The relationship between percent oxygen saturation and MeHg for the non-aerated treatments was significant ($r^2 = 0.75$, $p < 0.001$) with decreased percent oxygen saturation MeHg concentrations were increased.

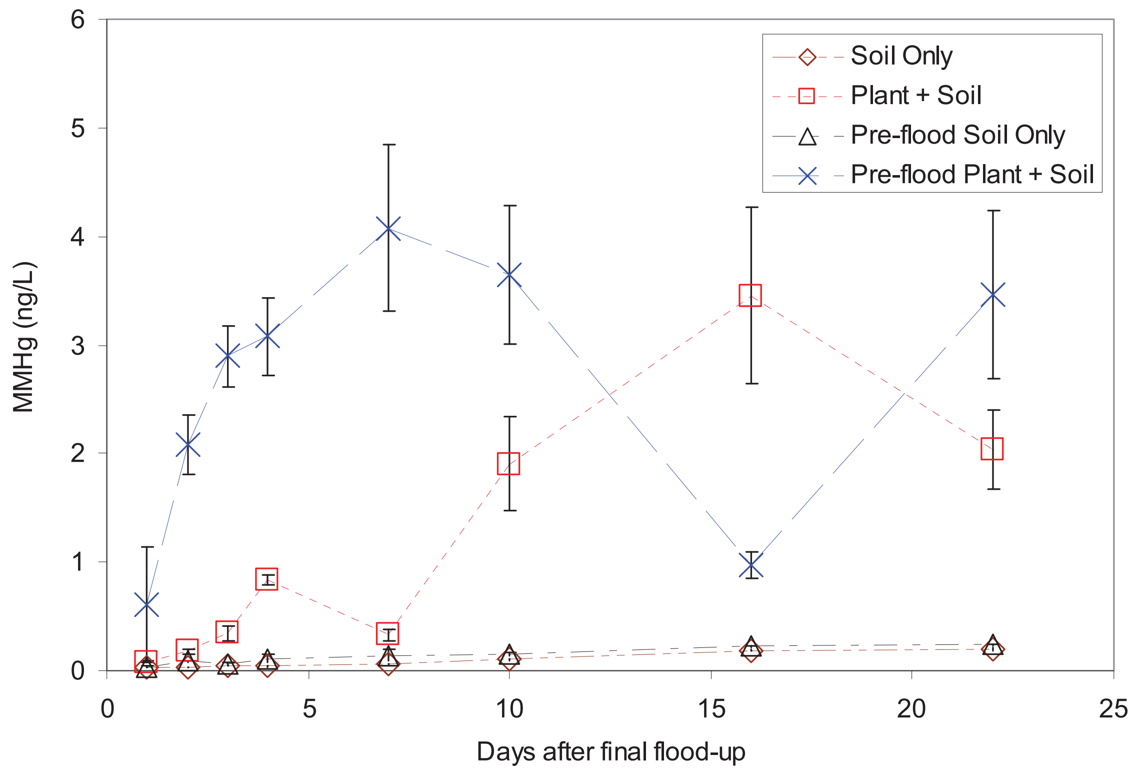


Figure 19. Average MeHg Concentrations over Time in various Microcosm Treatments

The data were analyzed using statistical methods with the following results: increasing sediment in microcosms does not produce more MeHg, increasing vegetation in microcosms results in more MeHg over the time frame studied, and aeration of microcosms reduced MeHg production.

2.7 Quantity of Water Discharged from Wetlands 112 and 123

The information in this Section is summarized from the Hydrology manuscript (Appendix **B**) and addresses (1) exchange between the wetlands and adjacent tidal sloughs and (2) internal mixing and constituent transport.

2.7.1 Exchange between Wetlands and Adjacent Sloughs

Tidal inputs and outputs to these wetlands exerted a greater effect than climate (evaporation and precipitation) during the field study. Additionally in Wetlands 112 and 123, FSSD inputs are managed by SRCD and the landowners to provide tertiary treated wastewater. This treated wastewater is a significant source of water for Wetland 112 during the fall.

Flood and drain events are the most significant hydrologic events for these wetlands. During the wetland flood period (beginning each fall and lasting into each spring), water levels in the wetlands are raised to fairly similar pond depths at the study sites and throughout much of Suisun Marsh, in order to manage for target waterfowl habitats. Field data indicate that Wetlands 112 and 123 varied their water levels roughly 0.25 ft during the flooding period. Consequently, wetland flood volumes on a per-acre basis are roughly similar between wetlands managed for similar waterfowl habitat conditions. Wetland 112, at 90 acres, has 35 to 113 acre-feet of water flooded onto it during each flood period and Wetland 123, at 210 acres, has 170 to 360 acre-feet.

The dramatic increases and decreases in water volume during the flood and drain periods are in stark contrast to the remainder of the fall and winter period during which water volumes change on the order of +/- 2 to 5% during each tide event. During this less fluctuating period, preferential flow would be expected along wetland ditches though on marsh plains the water is expected to be relatively quiescent with residence times expected to be on the order of many days to a few weeks.

In addition to the change in surface water volume, the soils go from unsaturated to saturated conditions during the first fall flood event. The soils in Suisun Marsh are very porous and our study wetlands had approximately 20 – 25% of pore space available for saturation. From the soils data for these wetlands (Appendix **A**), we predict 4 – 8 inches of water is required to saturate the soils.

The water additions from precipitation and losses due to evapotranspiration are minuscule when compared to tidal effects. Evaporation from early fall through late spring typically ranges from 0.5 to 0.8 inches per week. This hydrologic loss is an order of magnitude less than tidal losses. Precipitation is patchy and also relatively small in comparison to tidal exchange. Seasonally, Suisun Marsh averages about 25 inches of precipitation in comparison to tidal exchange of 4 – 11 inches per week at Wetland 123 and 3 – 8 inches per week at Wetland 112.

When considered in the context of the surrounding system, the hydrologic management of the wetlands impacts the surrounding sloughs most greatly during the fall. At that time of the year, the sloughs experience net upstream flow (Appendix **G** and Appendix **C**) and depressed DO levels. Reverse flow is likely a combination of minimal riverine runoff in this Mediterranean climate as well as the water demand from managed wetlands flooding. During the remainder of the flooded period (i.e., winter into spring), wetland hydrologic management impacts on the surrounding sloughs seems less because of more constant flow in the downstream direction and greater flow magnitudes.

2.7.2 Internal Mixing and Constituent Transport

The hydrology within the wetlands is characterized by short term water exchanges through water control structures on daily tidal cycle timescales (i.e., flood tide small inflows and ebb tide small outflows) and by the two-week spring-neap tidal cycles. These cycles result in tidal exchange onto and off the wetlands during each tide event. During the flood-up periods, water volume increases by about 20 – 120% during each tidal cycle over the volume present at the end of the previous flood tide cycle (i.e., the step-wise filling of the wetland with each flood tide). Once at fall management level, only about 5% of the water is exchanged during each tidal cycle.

Without a tracer, only the available hydrologic data (wetland and slough stage and wetland topography) can be used to estimate hydraulic residence times and constituent transport. The stations monitored in this study include stations located in the perimeter ditches and within sloughs, and stations located in the marsh plain. The ditch and slough stations are expected to be advection dominated systems with water moving preferentially through the sloughs and ditches and not being completely mixed. Packets of water are expected to move up and down these ditches depending upon the direction of flow. During ebb tides (wetland outflow to slough), water quality at these locations is expected to represent water quality from the wetland. During flood periods (wetland flooding from slough), water quality measurements are expected to represent slough water quality.

For marsh plain locations, we propose the system is more diffusion or dispersion dominated and more represented as a continuously mixed batch system. During flood tide inflow periods, water is assumed to spread over the marsh plain and become relatively well mixed with the existing water. During ebb tide outflow periods, the mixed water then discharges. Thus for these locations understanding the relative amount of water added is important in predicting the residence times and fate of constituents.

Figure 20 models the amount of tracer in the marsh water column versus the number of tidal exchanges that have occurred. This simple model assumes the marsh plain is well mixed and diffusion dominated. Water is applied and discharged in batches with water being added and removed uniformly across the marsh plain.

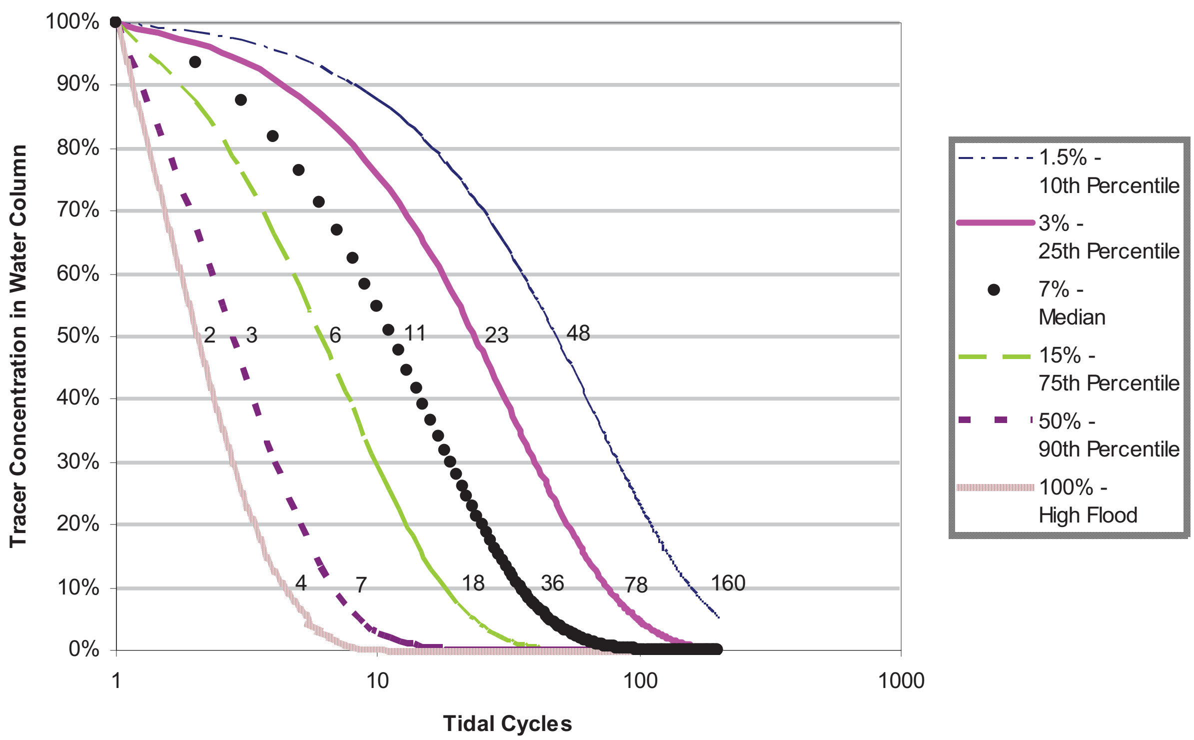


Figure 20. Estimating Mixing

Depending upon the amount of water as a percent of the initial water volume, a different number of tidal cycles are required to flush the tracer from the system. During much of the fall as discussed above, only around 5% new water is added per tidal cycle (the median exchange for the data set was 7%).

From **Figure 20**, the differences in the amount of water greatly affect the predicted hydraulic residence time. In periods of flooding during which 50 – 100% additional water is added onto the field per tidal cycle, the predicted tracer concentration changes in the water column greatly. Under conditions in which water volume in the marsh increases by 100%, the tracer concentration is halved after two cycles and is one tenth after about 4 tidal cycles. However, under conditions in which water volume added to the marsh is only 7% greater than the existing water volume, eleven tidal cycles are required to reduce the tracer concentration by half and 36 tidal cycles are needed to reduce it to one tenth.

Thus, for much of the season during which water levels are maintained relatively stable, water quality changes in the marsh plain occur primarily because of biogeochemical cycling or through evapoconcentration. Transport plays a minimal role in affecting water quality. Based upon the 25^{th} – 75^{th} quartile range, about 3 to 15% of the water is exchanged during most tidal cycles for periods during which water levels are maintained. Thus, the HRT for export of 50% of that water is estimated to be 6 – 23 tidal cycles, and for 90% of that water to be 18 – 78 days. However, during flood periods, water quality can change much more rapidly in the marsh plain with significant changes occurring simply from hydrologic transport in just a couple tidal cycles. Each tidal cycle is approximately ½ day.

2.8 Effect of Managed Wetland Discharges on Slough Water Quality

The information in this section is summarized from the manuscripts on Water Quality (Appendix **C**) and Hydrodynamic Transport (Appendix **G**). We have noted DO concentrations within Peytonia and Boynton sloughs remain low throughout the fall period (**Figure 13**). However, acute responses occur specifically following drain events. All drain events, regardless the season, result in acute drop in slough DO level (**Figure 13**). In this section we discuss both the chronic and acute low DO conditions. It should be noted that the operations of other managed wetlands along these sloughs may contribute to the DO responses observed within the sloughs (see **Figure 4** for map of other managed wetlands and other potential sources of low DO conditions in Peytonia and Boynton sloughs). However, since no wetlands aside from 112 and 123 were monitored, the extent of these contributions cannot be quantified.

2.8.1 Chronic Dissolved Oxygen Response

Figure 13 shows DO trends in Peytonia and Boynton Sloughs. The water quality standard for DO concentration (7 mg/L) is shown in the figure and dates identify when the sloughs are above and below the standard. DO concentrations are chronically below the standard from mid September through mid December. During this period, the sloughs have net upstream flows as discussed in more detail in Section 3.1. Consequently, during this period slough water is not being flushed in the downstream direction and thus respiration within the sloughs and ongoing wetland discharges with low DO continue to maintain low DO conditions in the sloughs. Once slough water begins flowing in the downstream direction, either from winter storms increasing exchange or wetland operations reducing the net upstream flows, the chronically low DO conditions end.

2.8.2 Acute Dissolved Oxygen Response

DO sags in the sloughs during drain events reflect six drivers: discharges of low DO and high BOD from any wetland connected to the slough, time since those discharges for BOD to drive further respiration, DO levels in source tidal waters, extent of net upstream flow and thus tidal mixing, rainfall if any, air and water temperature, and watershed flows if any.

Fall drain events from both wetlands appeared to affect DO concentrations in the sloughs. Immediately after each fall drain event from Wetland 123, DO levels in the sloughs drop steeply and oftentimes down between 0 and 2 mg/L during the drain event. Peytonia Slough in the north is generally more greatly affected. Fall drain events from Wetland 112 also coincided with dropping DO levels in the sloughs and those effects were greater in the second year of the study. Generally, DO drops of about 5 mg/L occurred when water was drained from Wetland 123 as compared to drops of about 2 mg/L when water was drained from Wetland 112 (Figure 13).

Late winter flushing events also cause DO sags within Peytonia and Boynton Sloughs, although these sags are less intense and of shorter duration than those accompanying fall drain events. DO levels in Boynton and Peytonia Sloughs drop by 1 – 2 mg/L following winter drains from Wetlands 112 and 123, but seldom did these lower DO below 7 mg/L. During this period net flows in the slough are in the downstream direction, likely resulting in water with low DO and high BOD being more easily flushed from the sloughs than during the fall when net upstream flows are common.

2.8.3 Loading of other Water Quality Constituents

The hydrologic results presented in Appendix **B** were combined with the water quality results presented in Appendix **C** to calculate loads of key constituents. From these calculations, Wetland 123 exported about 2.5 – 3X the amount of DOC (306 and 826 mg/m^2/inches of water/tide) and unfiltered MeHg (31 and 117 ng/m^2/inches of water/tide) than did Wetland 112. Regression plots suggest load exports were highest when wetlands were managed to drain as compared to periods they were managed to flood or to maintain maintenance flows; however, those results were not always statistically significant. When considering water volumes being exported from the wetlands, about two times more water is exported from

Wetland 123 than Wetland 112 which makes sense given that it is approximately twice the area. This result is true for all water management objectives and for both fall and late winter seasons. For this reason, total loads being exported per tide range were from about four to ten times higher for Wetland 123 as compared to Wetland 112. The greatest differences are during the periods in which wetlands are managed to drain. These estimates are standardized to wetland area. No actual measurements of DOC or MeHg were made in the sloughs themselves, so the response of the levels of these constituents to the above estimate loads cannot be known.

2.9 Ecological Community Shifts and Population Changes in the Aquatic Fauna in Peytonia, Boynton, and Suisun Sloughs

The information in this Section is summarized from the Aquatic Ecology manuscript (**Appendix D**). The composition of fish assemblages in Suisun Marsh change monthly and annually as fish migrate, as reproductive success of different species varies, and as freshwater inflow, salinity, and temperature change (O'Rear and Moyle 2008, 2009). Despite this variability, there is a core of species (e.g., juvenile striped bass and tule perch) that are found in the marsh all year and respond to local conditions such as low DO levels created by wetland outflows. The immediate effect of these low DO events is to eliminate the fishes and invertebrates in the sloughs affected (Schroeter and Moyle 2004; O'Rear et al. 2009). While DO levels in smaller sloughs such as Peytonia and Boynton can recover within a few weeks following a low DO event, it may take months before they are repopulated by desirable fishes. Here are some basic observations from the UC Davis fish sampling program to show this:

- Fishes that cannot tolerate low DO make up a smaller proportion of the community during fall and winter in Peytonia Slough and Boynton Slough (e.g., tule perch were virtually absent in 2009, but they were still common in upper Suisun Slough, which had higher DO levels).
- In Peytonia Slough and Boynton Slough, lowest catches are usually in fall months (Oct-Dec), while in other sloughs (e.g., Suisun) lowest numbers are usually in late winter or spring.
- While catches drop in all sloughs when the water gets cold, they drop more in smaller sloughs with multiple wetland outfalls. In 2008, for example, Denverton Slough, lower Suisun Slough, and First Mallard Slough, which have few or no outfalls, contained a diverse assemblage of fish in autumn and winter, including desirable or listed species that require higher (>5 mg/l) DO levels (e.g., striped bass, longfin smelt); in contrast,

Peytonia Slough and Boynton Slough at the same time had smaller numbers of fish, and most were low-DO-tolerant species (e.g., black bullhead, white catfish, common carp; O'Rear and Moyle 2009).

- In 2009, tule perch were present in fair numbers in all sloughs during the duck-pond operating season except in Peytonia Slough, Boynton Slough, and upper Goodyear Slough (which also has DO issues).
- A low DO event in upper Goodyear Slough in October 2009 resulted in mortality of many fishes, which included adult striped bass, splittail, and bluegill. (O'Rear et al. 2009).

3 Conceptual Model of Key Processes Affecting Tidal Slough Low DO Generation

In order to develop best management practices aimed at reducing or eliminating the occurrence of low dissolved oxygen events in the perimeter tidal sloughs in Suisun Marsh, we have developed a simple conceptual model. This model, shown graphically in Figures 21 through 24, describes the key processes that this study indicates may be the primary drivers of low DO and thus represents the potential points of intervention through BMPs.

3.1 Conceptual Model Diagrams

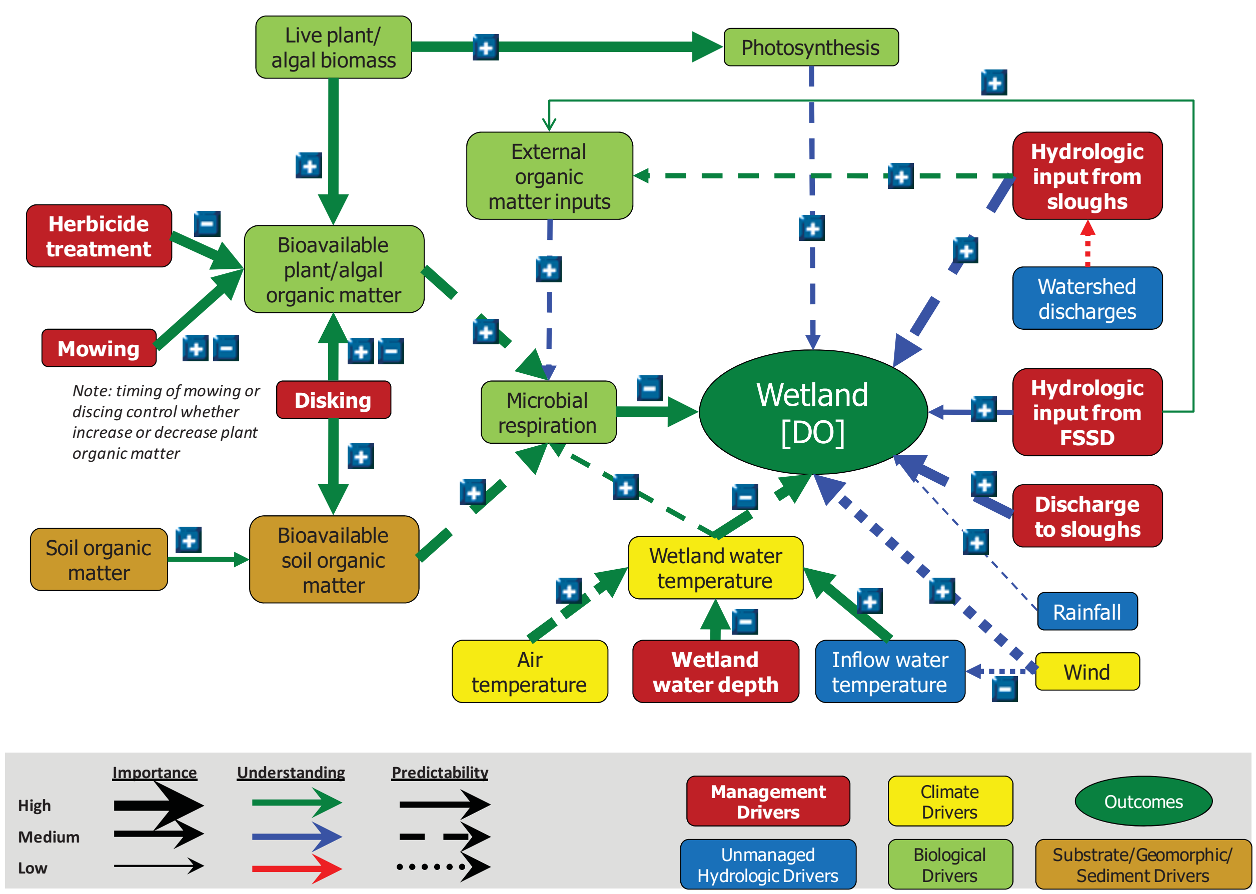


Figure 21. Conceptual Model Diagram for Wetland Dissolved Oxygen Concentrations

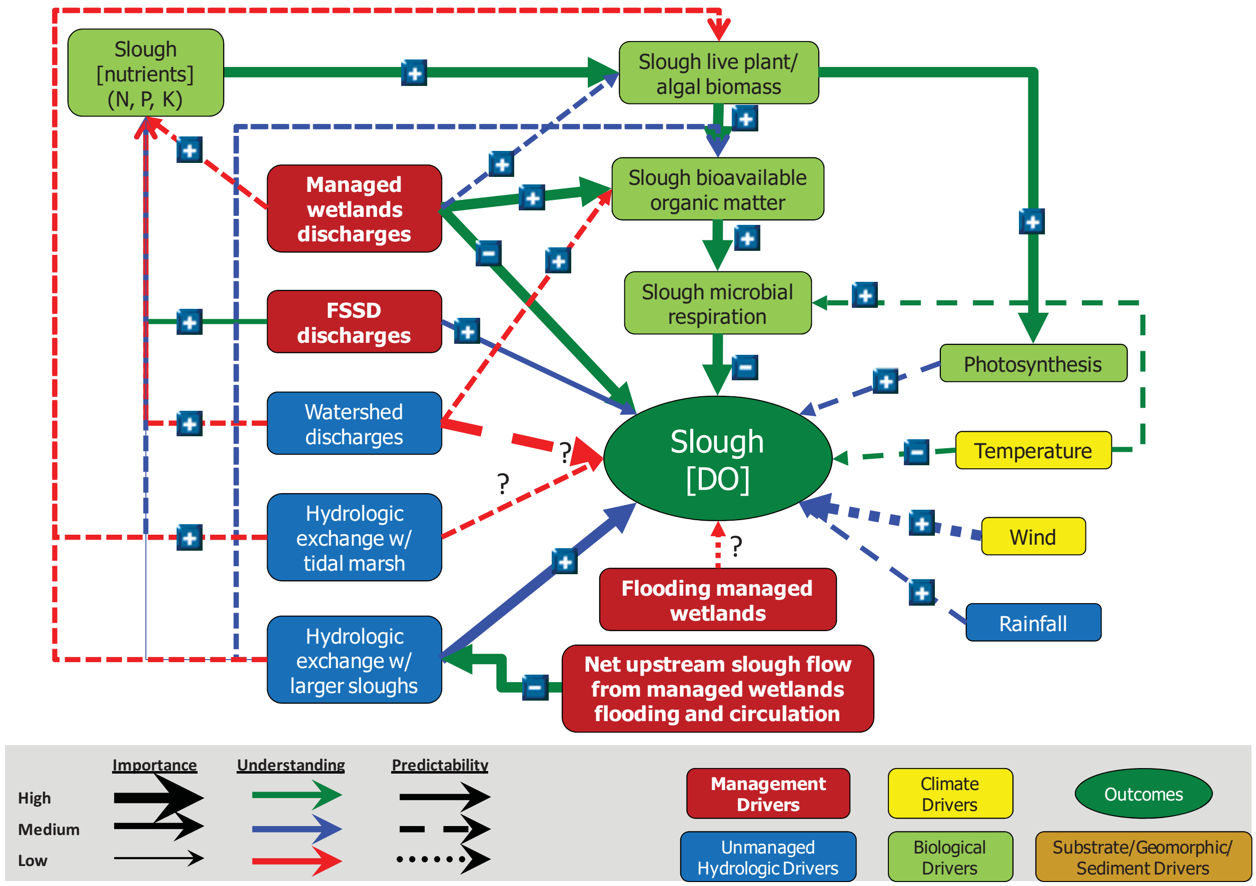


Figure 22. Conceptual Model Diagram for Slough Dissolved Oxygen Concentrations

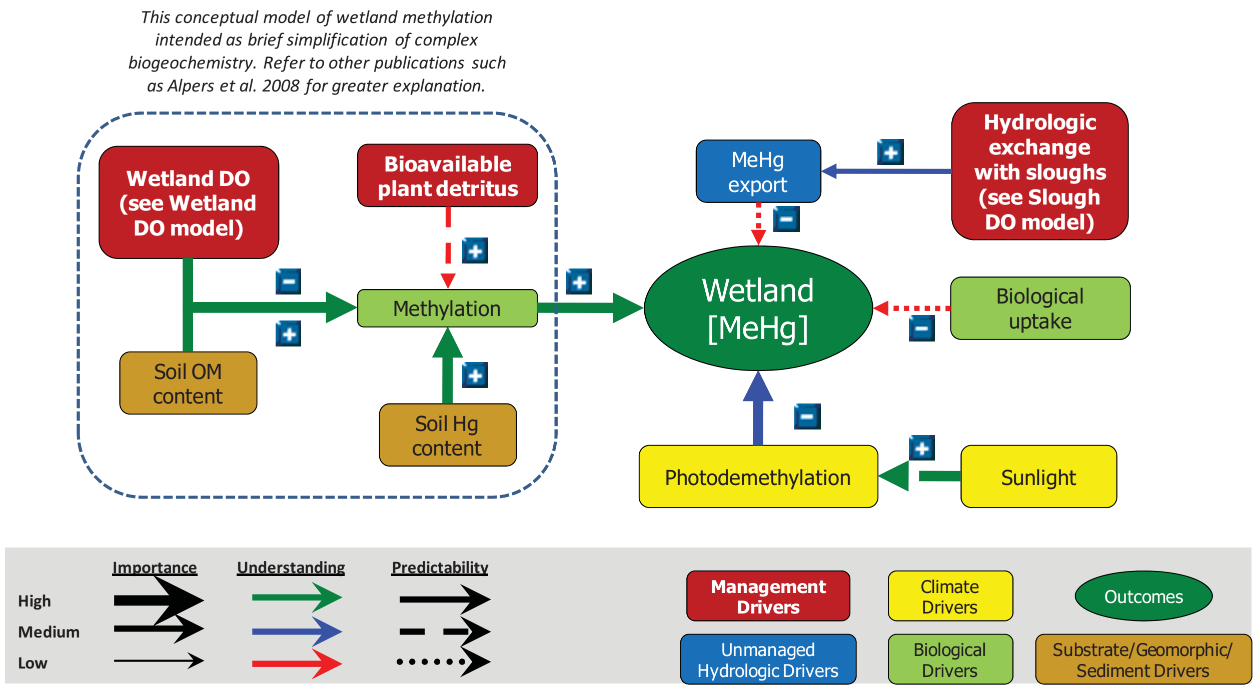


Figure 23. Conceptual Model Diagram for Wetland Methylmercury Concentrations

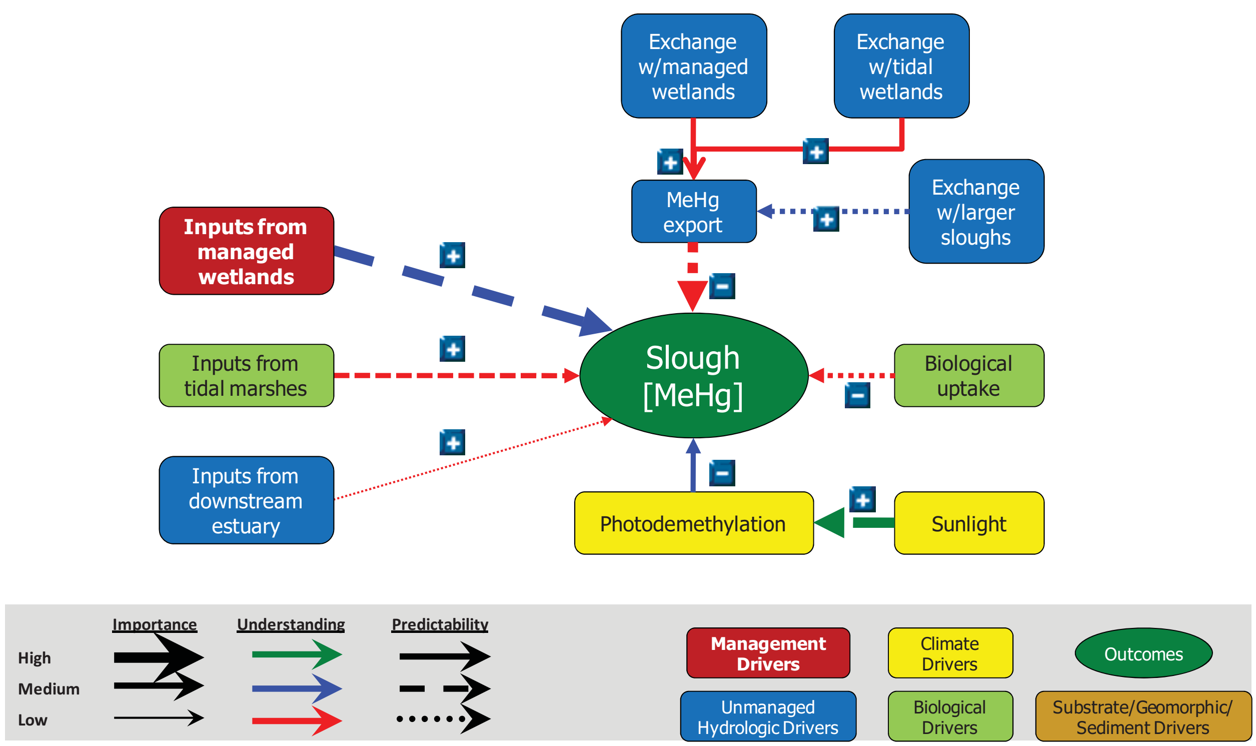


Figure 24. Conceptual Model Diagram for Slough Methylmercury Concentrations

** As with Figure 23, this diagram greatly simplifies methylmercury biogeochemical processes.*

3.2 Key Management Drivers

The four conceptual model figures above each indicate *management drivers* that we have identified as important influences on low DO and MeHg conditions. Below we discuss these drivers.

3.2.1 Reducing Net Upstream Flow in Peripheral Sloughs during the Fall and Early Winter

DO sags in the studied sloughs correspond directly with all wetland drain periods, whether they occur in fall or winter. The studied managed wetlands experience a number of flooding and draining events in the fall and winter for different wetland management reasons. Early fall flooding at each wetland has the greatest water demand because of the need to saturate the soils in addition to raising surface water levels. The early fall flooding at the studied managed wetlands, and other wetland units along the sloughs, creates this large water demand which in turn contributes to net upstream flows at Boynton and Peytonia Sloughs. Net upstream flow hinders the flushing of BOD from the system and the dilution of low DO slough water with other water sources.

Discharging into the sloughs during this period of time exacerbates any water quality problems because there is inadequate flow in the downstream direction to push the low DO and high DOC/MeHg water out. Rather, movement through the slough is slow and the discharged water lingers. Temperatures are typically higher at this time of year, leading to reduced DO capacity in all waters as well as accelerated respiration rates by aquatic microorganisms (further reducing DO concentrations). These flow conditions contribute to chronically low DO levels in Boynton and Peytonia sloughs during the fall. Tidal mixing in any peripheral sloughs in Suisun is always somewhat limited but the managed wetland-induced net upstream flows have a demonstrable adverse effect on tidal mixing in these sloughs.

Thus, in sloughs experiencing low DO problems, avoiding/reducing drainage into the sloughs during the fall, or coordinating wetland discharges among wetland managers so that no two wetlands are flooding/discharging to the sloughs during the same time period should help to reduce the occurrence and severity of low DO events.

3.2.2 Water Quality Associated with Large Drain Events

Fall and winter drain events result in immediate decreases in DO concentrations at perimeter stations around the wetlands. During fall events, DO levels are near or at 0 mg/L with little diurnal variation. DOC, methylmercury and SUVA levels all spike during the early fall flooding and subsequent drain. Thus, these fall events are characterized by organic carbon loads drawing down DO levels in the managed wetlands. Winter drops are less severe. These events translate to large DO drops in both Boynton and Peytonia sloughs, which result in low fish numbers, either through fish kills or through fish leaving sloughs to avoid low DO water. Targeting approaches that reduce the magnitude and duration of the low water quality associated with managed wetland drain events is expected to yield a demonstrable improvement in slough water quality.

3.2.3 Managing for High Wetland DO Levels to Minimize Mercury Methylation

Methylmercury concentrations are most affected by dissolved oxygen levels. With DO levels above a certain threshold, methylmercury production is expected to be repressed. Data from this study suggests that threshold is between 1 and 4 mg/L. These low DO waters tended to have DOC levels above 40 mg/L suggesting a link between the two constituents. Thus, actions that can maintain DO levels above these thresholds may have beneficial effects at reducing methylmercury production in the managed wetlands.

3.2.4 Manage DOM Sources in Managed Wetlands

Results of this study suggest that the bulk dissolved organic matter (DOM) pool in these wetlands is dominated by soil and plant derived material. Summer wetland plant growth and management provides high levels of organic matter that fuels biological oxygen demand that lowers DO levels and triggers mercury methylation conditions. As time passes in the fall, DOM shifts its composition to a less humic, plant derived OM which indicates that labile soil carbon DOM is consumed in the first few weeks of flooding as biological and photochemical processes take place. The affected water in the wetlands then is discharged into the tidal sloughs as part of fall flood-up and early water circulation activities, introducing these water quality constituents into the tidal environment. Approaches that reduce availability of labile organic carbon especially in the fall flood-up period may help to reduce low DO and high MeHg conditions.

The fall flood-up period also corresponds with activities that result in high DOC export. Vegetation management (mowing and discing) occurs in summer months, providing a ready source of organic matter. Project data (Appendix **F**) suggest that microbial vs. photochemical processes dominate the processing of this organic matter and it is that microbial respiration that leads to depressed DO levels. The flushing of water across the wetlands allows DOC to be exported from these sources. This study did not examine the biogeochemical processing of this DOC once exported into the tidal sloughs so we can hypothesize only that once in the sloughs microbial activity continues to consume this DOC and thus continue to lower slough DO levels. However, study data does allow indicate strongly that there is a sufficient carbon pool within the wetlands throughout the fall to support ongoing generation of low DO waters that discharge to the tidal sloughs as part of wetland water circulation. Accompanying the low DO sags, are elevated levels of MeHg. The results of our study indicate that DOC and MeHg levels within the managed wetlands decrease markedly by December, likely due to microbial and photochemical degradation processes. DO levels also improve due to internal mixing and reduction in ambient temperatures. Thus, in sloughs experiencing low DO problems, avoiding/reducing drainage into the sloughs during the fall, or coordinating wetland discharges among wetland managers so that no two wetlands are flooding/discharging to the sloughs during the same time period should help to minimize the amount of DOC and MeHg exported in the sloughs and provide additional time for DOC to become broken down into more recalcitrant forms that have a lower BOD.

Importantly, winter flushing has a lesser effect on slough DO concentrations than in the fall because background DO in the sloughs are higher and water quality within the wetlands has improved from fall conditions. Thus, flooding in the winter to leach salts appears to have reduced negative impacts and can help maintain normal soil salinity. Coordination among wetland managers to ensure non-overlap of flushing events in sloughs experiencing low DO problems would help to reduce these impacts even more.

3.2.5 Effects of Wetland Vegetation Management Strategies on Water Quality

Monitoring stations on the wetlands near areas in which mechanical land preparation occurred (i.e., mowing, discing) tended to have higher SUVA or DOC levels during either the flooding or draining period though these differences were not statistically significant. During the fall and winter circulation periods (i.e., no major flood/drain events), no such trend was evident. Comparing the two study sites allows additional insight on effects of different wetland vegetation management approaches, though the small sample size and short study duration leave open the significance of the differences. Over the summer 2008 period, Wetland 123 had about 20% of its land disked and Wetland 112 had about 40% mowed. Fall flooding events at Wetland 123 resulted in much higher DOC and MeHg spikes than did at Wetland 112. These data suggest: (1) vegetation management approaches may affect the amount and labile extent of organic carbon, (2) discing may be exacerbating organic carbon exports and low DO events through greater disturbance of the soils and thus greater soil carbon availability, and (3) the effects are relatively short-lived lasting only a few weeks.

Tilling soils increases oxidation of the organic matter leading to its release when the system is re-flooded. The SUVA data support a compositional shift that reflects mixed soil and plant-based carbon during initial fall flood-up to a more plant-dominated carbon pool after a few weeks when wetlands have transitioned to fall circulation operations. This phenomenon has been observed in studies in Wilson and Xenopoulos (2009) as well as studies comparing conservation and standard till practices (Lundquist et al 1999; Pellerin et al. 2009). Mowing produces a large amount of dead organic matter that, when wetlands are flooded, contributes to the organic carbon pool. The decomposition of organic matter from both mowing and soil disturbance appears to lead to DO sags and subsequent MeHg spikes within the wetlands. In contrast, research from the Yolo Bypass Wildlife Area found no difference in the 'first flush' MeHg or DO between tilled and vegetated fields though that study had a limited number of fields (Mark Stephenson, pers. comm.). In other words, further evaluation of the effectiveness of tilling practices is necessary.

Based upon this body of information and the results of our study, land management practices that minimize disturbance to soils and reduce the amount of dead, mowed vegetation present on the wetland surface at the time of fall flood-up are recommended to reduce impacts to water quality. Soil management could be conducted using conservation tillage practices (tillage method which leaves a minimum of 30% standing crop residue and reduces disturbance to the soil) over standard practices. Vegetation management could be altered by (1) favoring herbicide application over mowing to control undesirable vegetation, or (2) removing undesirable vegetation from the wetlands using methods such as livestock grazing or mechanical removal (bale and off-haul). Any mowing or tilling that does occur should be done as early in the management season as possible to allow maximum decomposition of organic matter prior to fall flood-up.

3.2.6 Beneficial Effects of Wastewater Effluent on Wetland Water Quality

Wetland stations with tertiary treated wastewater inflows had low DOC and SUVA levels and high DO concentrations. These effects were not noticeable at nearby stations away from these inflows. These results suggest (1) the tertiary treated water is high quality water with less BOD than marsh waters and (2) wetlands BOD consume available DO from all source waters. Thus, the greater quantity of high DO waters available to the managed wetlands the less potential for developing low DO conditions.

3.2.7 Relative DOC Loading as Function of Wetland Water Exchange Rates Not Clear

Wetland 112 discharged an estimated load of 75 to 120 mg-DOC/m^2/tide event and Wetland 123 discharged an estimated load of 155 – 1117 mg-DOC/m^2/tide event. Higher DOC discharge rates at Wetland 123 were attributed to higher DOC concentrations in the wetland and higher discharge rates through the wetland; which factor dominates cannot be discerned with data from this study. Though flows through Wetland 123 were higher than through Wetland 112 during the study, the available data do not allow assessment of whether the higher flows result in lower DOC concentrations. This question may lend itself well to simple hydrologic modeling prior to any field pilot studies.

3.2.8 Temperature

Temperature does not appear to be a good indicator of DO levels in the sloughs because the lowest DOs occur when temperatures are dropping, indicating that the increased DO saturation capacity of lower water temperatures is overwhelmed by loadings of low DO and high BOD waters. This suggests temperature management, for which limited approaches are available, may not be the most effective strategy. Wetland water depth is the primary management tool and the study data suggest that guiding wetland water depth to manage for water temperature may not yield sufficient benefits to pursue.

4 Best Management Practices

This chapter discusses a variety of Best Management Practices (BMPs) intended to help minimize low DO problems in Suisun Marsh sloughs and by associated to reduce methylmercury production and loading into the aquatic environment. Some of these BMPs were developed previously and implemented in certain locations and others are newly developed as part of this study. Many BMPs are recommended for further evaluation and use while some we recommend not be employed either for adverse effects on low DO and MeHg or because they would interfere substantially in achieving fundamental wetland management objectives. The intent of this chapter is to describe the goals and objectives of the possible BMPs (section 4.1), discuss a variety of logistical considerations that influence the relative feasibility of any BMP (section 4.2), summarize the two broad types of BMPs (section 4.3), and present and discuss the full range of BMPs in groupings of relative priority for further evaluation (section 4.4).

4.1 Goals and Objectives of BMPs

BMP goals consist of the intended ecosystem and regulatory outcomes following implementation:

- Achieve compliance with Basin Plan three-month 80% saturation standard
- Avoid any occurrences of fish kills
- Support removal of Suisun from 303(d) list for low DO and mercury

BMP objectives address the mechanisms that control low DO and MeHg production and discharge and BMP feasibility:

- Reduce creation of BOD, low DO, and MeHg within the wetlands
- Reduce discharge of low DO, high DOC, and high MeHg waters from wetlands to tidal sloughs
- Improve mixing of discharges to increase dilution
- Allow continued existence of properties as managed wetlands
- Be sustainable over time

4.2 Logistical Considerations Associated with BMPs

There are several logistical situations that must be considered when evaluating the potential implementation and effectiveness of BMPs. These situations vary based on individual managed wetland characteristics and location within Suisun Marsh. The primary logistical considerations are discussed below.

4.2.1 Wetland Elevation and Infrastructure to Flood and Drain with the Tides

Hydrologic management of the managed wetlands depends upon many factors. Key factors are wetland elevation relative to tidal elevations and the infrastructure for hydrologic management.

Wetland 123 and 112 are relatively high elevation wetlands. These wetlands have the ability to drain very quickly and therefore duration of submergence is readily limited. This, along with the low salinity water that is also available to these two wetlands, encourages a diverse and highly productive vegetative community. Low elevation managed wetlands have greater difficulty draining and have difficulty in limiting their duration of submergence. This results in less vegetative productivity but also makes it more difficult to conduct leach cycles which may lead to higher soil salt levels and therefore limit the plant community to more salt tolerant species.

In addition to the wetland elevation issues, infrastructure also affects the ability of the managed wetlands to manage hydrology. This infrastructure can include gates, pipes, flashboard risers and pumps as well as the ditch system that moves water through the wetland. These systems are relatively simple, geographically distributed, and non-mechanized. These characteristics limit the ability of managers with regard to the sophistication of water management. Any upgrade to water control structures and related infrastructure for any number of reasons (e.g. more precise control, automation and controls, overcoming elevational limitations) will require investments beyond what land managers may be able to afford. Possible resources to offset the investment costs can be the use of federal Environmental Quality Incentives Program (EQIP) funds which are used to improve resource conservation. More information is needed to understand the possible availability of these funds for managed wetland improvements.

4.2.2 Mosquito Control

Suisun Marsh is located near several large population areas including Fairfield, Suisun City, and Benicia. As such, the Solano County Mosquito Abatement District (Mosquito District) regularly monitors mosquito production in managed and tidal wetlands throughout the marsh. Mosquito reproduction can occur in standing water in most any wetland area. Thus, the Mosquito District works closely with landowners to regulate the timing and duration of water application on managed wetlands in Suisun Marsh, especially at initial flood-up during the warm fall months. If mosquito production becomes problematic, the Mosquito District either requires the landowners to flush the wetlands (drain and re-flood), or pay for treatment of their property with larvasides. As larvaside treatments are very expensive, hydrologic management is the preferred method for addressing mosquito issues. The cost per acre in 2010 was about $15/acre for aerial treatment with a juvenile growth hormone, pre-treatment (prior to flooding) with a pellets was about $88/ac. These costs are expected to rise considerably in 2011 and perhaps beyond and perhaps take longer to accomplish; the pilot who treated Suisun Marsh crashed in early 2011 in the Delta and did not survive. To date, SCMAD currently can't find anyone to treat the wetlands except a helicopter company. Costs may come back down if airplane treatment can be re-established. Thus, mosquito control could affect the ability to implement certain hydrologic management BMPs.

4.2.3 Time-of-Year Suisun Diversion Restriction

Restrictions are placed on water diversions in certain areas of Suisun Marsh at certain times of the year to protect fish populations. These restrictions will affect the ability to implement certain hydrologic BMPs in the restricted areas. The diversion restrictions are as follows:

- For Chinook salmon:
  - **Feb 21 - Mar 31**: 0% open
  - **Nov 1 to ~ Feb 1** (last day of duck hunting season): 25% open
  - Locations: Montezuma Slough, Nurse Slough, Denverton Slough, Cutoff Slough, Suisun Slough up to Goat Island, and open waters around Chipps Island and Van Sickle Island
- For Delta smelt:
  - **Apr 1 – May 31**: 20-35% open (%open based on results of CDFG 20-mm trawl surveys at sites 606, 609, and 610)
  - Locations: Montezuma Slough, Suisun Slough up to Goat Island, Goodyear Slough, Denverton Slough, Nurse Slough, all open water bays.

These restriction periods set the upper limit on how much water can be cycled through certain managed wetlands at the specified times of year. These restrictions also direct greater diversions off the smaller perimeter sloughs which can exacerbate net upstream flows and the resulting degraded water quality within those perimeter sloughs.

4.2.4 Wetland Management Objectives

The goals of wetland management and habitat improvement are to provide wintering waterfowl food and habitat, provide breeding habitat for resident waterfowl and ground nesting birds, and to preserve open space while maintaining landowners hunting opportunities and experiences. It is assumed that managing wetlands to maximize waterfowl food plant quantity and diversity will maximize wintering waterfowl numbers in Suisun. The ability to manage water is the key to achieving managed wetland goals. Water managers must continuously adaptively manage their properties in order to achieve management objectives.

Land managers use vegetation manipulation, in conjunction with water management, as a tool to create a mosaic of habitats desirable to waterfowl species. Vegetation manipulation may include, but is not limited to, planting, herbicide treatment, flooding, burning, discing, and mowing.

Wetland maintenance and habitat improvement in Suisun relies on the following principles: Hydrologic change influences plant community composition and structure, thereby affecting the availability of waterfowl food (Fredrickson and Laubhan 1994). The quality, abundance and availability of resources, as well as spatial arrangement of different wetland types that provide such components, are critical factors that determine abundance and biodiversity of wetland wildlife (Fredrickson and Laubhan 1994).

Wetland managers can have the greatest effect on food resources and resulting wildlife use using these principles. Diverse wetland types and their spatial arrangement in the region determine the level of wildlife use. Dynamic wetlands supply a variety of food resources that allow waterfowl to feed selectively and to obtain nutritionally adequate diets from a variety of sites (Fredrickson and Reid 1988). In Suisun it is the diversity of habitats and the variety of foods they produce that attract up to 28% of the wintering waterfowl in California and many resident waterfowl.

Wetland managers maintain and improve local upland areas for resident breeding and nesting waterfowl where appropriate. Upland fields in the Suisun Marsh (specifically Grizzly Island Wildlife Area) are productive mallard nesting areas (McLandress et. al. 1996). Current management strategies maintain and enhance waterfowl nesting and brood habitats to promote local waterfowl production. More than 60% of the mallards harvested in California originate from breeding areas in California. Factors limiting mallard numbers in California are related to the quantity and quality of mallard nesting and brood rearing habitats (California Waterfowl Association, 2003).

4.3 Available Management Tools and Mechanisms Targeted

We have identified a finite suite of tools available for developing BMPs; **Table 5** links the mechanisms to be targeted by the BMPs to the importance of that mechanism and the available management tools.

Table 5. Available Management Tools Relative to Mechanisms Targeted

Low DO and MeHg Mechanisms Targeted by BMPs	Why Matters	Available Management Tools
Organic matter pool available at fall flood-up	Predominant source of BOD that influences DO levels and mercury methylation	Summer/fall approaches to: • Vegetation management • Soil management • Water management
Quality of supplied water	Affects assimilative capacity of water within wetlands	• Wetland intake locations • Intake and discharge timing of multiple wetlands on a given slough • Use of FSSD supply
Residence time of applied water	Affects organic matter decomposition and thus DO levels and methylation chemistry including demethylation	• Flood-drain regime at fall flood up • Rate of water exchange between wetlands and sloughs after flood up • Internal wetland circulation
Mixing in tributary sloughs	Affects water quality	• Intake and discharge locations of multiple wetlands on a given slough • Intake and discharge timing of multiple wetlands on a given slough • Use of FSSD supply

4.4 Evaluation Criteria

We have identified a number of evaluation criteria or *performance metrics* for the BMP goals and objectives:

Slough water quality conditions

- Effect on DO concentrations
- Effect on DOC concentrations
- Effect on MeHg production and loading

Mixing in tidal sloughs

- Extent to which promotes net upstream flow in perimeter tidal sloughs

Factors that affect wetland management targets

- Water quality especially avoidance of internal low DO conditions
- Vegetation cover and community composition
- Access for performing maintenance

Sustainability

- Dependence on ongoing levee maintenance
- Use of gravity vs. pump-driven flood/drain
- Effects on wetland subsidence

Information Value

- Degree to which BMP implementation, when subject to scientific evaluation, can provide a high information value to understanding the underlying problems and the role of different approaches to their resolution

4.5 Best Management Practices

The BMPs are organized into four groups:

1) Water management: initial fall flood-up period
2) Water management: fall-winter circulation period
3) Water management: spring and summer salinity and vegetation management
4) Vegetation and soils management

Table 6 (at the end of this section) presents the full suite of BMPs and summarizes their intended outcomes, how they perform relative to the evaluation criteria, whether they should be evaluated further, and recommendations on whether or not the BMP should be put into use.

In practice, it may be appropriate to implement more than one BMP concurrently. Where clear, we have identified synergistic BMPs. Other synergies may well exist that we have not identified and innovation based on good science is highly encouraged. BMP implementation feasibility is likely to vary from one wetland to the next, so it is important that prior to selecting and implementing BMPs, the landowner work with SRCD and other science advisors as necessary to promote appropriate BMP implementation.

The following BMP's were developed to address the sites in this study and other sites in Suisun Marsh that may play a role in contributing to low DO and/or elevated MeHg conditions. These

BMP's can be implemented as appropriate based upon the physical constraints, management objectives, and infrastructure at each site.

4.5.1 Water Management BMPs: Initial Fall Flood-Up Period

BMP H-1. Pre-Flood to Fall Management Level, Drain, Immediate Re-flood

Description

This BMP consists of a fall flood-up cycle involving flooding to fall management level, draining, and immediately re-flooding the wetland to fall management level. The rationale behind this BMP is that flooding the wetland surface will initiate the vegetation decomposition process, saturate the soils, and establish flow paths within the wetlands, which should help to reduce the production of low DO hotspots within the wetland. This practice was begun in 2000 at Wetland 123 and was the practice used at Wetlands 112 and 123 during the first year (2007).

Evaluation Summary

The data show this practice resulted in large spikes of DOC, MeHg and SUVA into the sloughs during the first flush and led to acute DO drops at the wetlands and within the sloughs. This practice should be discontinued. No additional study is recommended for this BMP. Eliminating this practice is likely to increase vector control costs and may increase the expense associated with salinity management. Targeting winter methods to manage salinity may mitigate salinity challenges.

Further Study

No additional study is recommended in relation to low DO conditions. For its role in MeHg contributions, further study may be appropriate for those wetlands whose discharge waters are situated onto larger sloughs that do not experience the low DO problems. The purpose of such investigation would be to determine whether in the absence of contributing to low DO problem that these discharges might still be contributing to food web exposure to MeHg.

Use Recommendation

Do not use at wetland sites where discharge water goes into small sloughs with potential for low DO. Whether this practice should be continued on wetlands that discharge to larger sloughs where MeHg might still be of concern should be subject to further evaluation.

BMP H-2. Pre-Flood to 'Field Saturation Level', Drain, Delayed Re-Flood

Description

This BMP consists of a fall flood-up cycle involving flooding to a water level sufficient to barely submerge (i.e., "wet") the wetland surface, immediately draining, and then re-flooding the wetland to fall management level after a period of 5-10 days. The rationale behind this BMP is that briefly wetting the marsh plain will stimulate aerobic breakdown of organic matter on the marsh plain during the subsequent 5-10 day dry period, thus reducing BOD in the system during the second flood-up period. The smaller pre-flood water volumes reduce magnitude of low DO and high BOD pulse into the adjacent slough system upon initial drain. Wetlands 112 and 123 implemented this BMP in 2008.

Evaluation Summary

The data show large DOC, MeHg and SUVA increases in the wetland water column during the initial flooding and large BOD as demonstrated by the sharp drop in water column DO concentrations during this time and immediate effects on slough DO when wetland water was discharged. Lab experiments for methylmercury showed no improvement using a pre-flood up management strategy. This practice was unsuccessful in sufficiently decreasing DOC being discharged during the first fall flush and also has the potential for increased vector control costs and multiple abatement treatments. This practice should be discontinued. No additional study is recommended for this BMP.

Further Study

No additional study is recommended.

Use Recommendation

Do not use at wetland sites where discharge water goes into small sloughs with potential for low DO. Whether this practice should be continued on wetlands that discharge to larger sloughs where MeHg might still be of concern should be subject to further evaluation.

BMP H-3. Pre-Flood to 'Field Saturation Level', Drain, Immediate Re-Flood

Description

This BMP consists of a fall flood-up cycle involving flooding to a water level sufficient to barely submerge (i.e., "wet") the wetland surface, draining, and immediately re-flooding to fall management level. The rationale behind this BMP is that briefly wetting the marsh plain will prevent a large low DO pulse into the adjacent slough system during the first flush. This practice is a modification of BMP H-2 that was implemented in 2008 at Wetlands 112 and 123.

Evaluation Summary

The results of the study indicate that BMP H-2 was unsuccessful at sufficiently decreasing DOC being discharged during the first fall flush. Since this BMP is similar to H-2, but will allow less time for breakdown of organic material between flood events, it appears likely to support discharge of even greater BOD into tidal sloughs and thus is even less likely to address water quality concerns than BMP H-2. This practice should not be implemented.

Further Study

No additional study is recommended.

Use Recommendation

Do not use.

BMP H-4. Flood and Hold with Minimal Exchange

Description

This BMP is similar to the baseline management practice of flooding the wetlands without an immediate post-flood drain event, only under this BMP the exchange of water with the adjacent sloughs is reduced or eliminated during the fall when water quality conditions within both the sloughs and wetlands are poorest. The rationale behind this BMP is that eliminating discrete drain events and reducing exchange between the wetlands and sloughs during the fall months will isolate poor quality water within the wetlands when sloughs are most susceptible to impacts from wetland discharges. It should also allow for photodemethylation and microbial degradation of DOC to take place in wetland waters, thus lessening the impact of these constituents upon slough WQ when released. This BMP has not been evaluated in the field.

Evaluation Summary

This BMP should eliminate the acute drops in slough DO associated with wetland drain events and circulation operations during the fall. However, implementing this BMP may decrease wetland water quality (DO, salinity) over current conditions due to reduced exchange. This low quality water could potentially impact wetland biota, cause a nuisance to landowners (black water, foul odors, etc.), make vector management more costly, and increase wetland salinity, potentially requiring additional salinity flood/drain events (higher costs due to need for additional labor) in the winter-spring.

Further Study

This BMP lends itself to two parallel lines of investigation regarding its potential efficacy: (1) its efficacy at improving water quality conditions in tidal sloughs and (2) the nature of potential adverse consequences to water quality and associated functionality of the wetland as waterfowl habitat including mitigating approaches if adverse wetland water quality conditions or habitat degradation occur.

Use Recommendation

Could potentially be used if wetland management issues can be resolved. Likelihood of resolving those wetland management issues does not appear to be high.

BMP H-5. Delay Fall Flood-Up as Late as Possible

Description

This BMP involves flooding wetlands as late as possible in advance of the fall waterfowl management and hunting season. The rationale behind this BMP is two-fold. First it is aimed at having flood-up occur when water temperatures are as low as possible in order to limit temperature-dependent microbial activity and to increase DO saturation capacity of the water. It is based on the premise that air temperatures will be cooler as fall progresses and that water temperature is driven largely by air temperature. Second it may have a minor benefit of allowing more time for decay of organic matter on the wetland surface though this process is slow when soils are dry. This BMP has not been evaluated in the field.

Evaluation Summary

Our data shows water temperatures drop approximately 1.5 – 2.5 deg C per month during the fall (September through November). Though biogeochemical processes are typically exponentially affected by temperature, this effect is still relatively small during the fall period when temperatures drop from about 18 – 19 deg C in mid September to about 16 – 17 deg C in mid October. Also, the data from this study do not suggest temperature is limiting in BOD availability. A major disadvantage of this BMP is that it would compress the time period over which a suite of wetlands on a given slough divert water, leading to a concentrated period of net upstream flow which typically exacerbates slough water quality issues. It may also hinder normal wetland management operations and reduce habitat available for early migrating waterfowl and shorebirds. To maximize its effectiveness and minimize its impacts on wetland management, close coordination between multiple wetlands would have to take place during fall flood up period.

Further Study

This BMP may warrant further exploration if the level of multi-wetland management coordination could be achieved. Before this approach should be considered, a modeling exercise would be needed to assess how altering the timing and magnitude of flooding throughout this system affects upstream flow and mixing conditions in the sloughs, in order to validate its potential effectiveness. If modeling shows promise, then field evaluation would require a careful study design to separate natural vs. management factors.

Use Recommendation

If modeling indicates a benefit, then consider for trial period.

BMP H-6. Re-Route Wetland Drain Events to Larger Sloughs

Description

This BMP involves reducing the impacts of wetland discharges on small sloughs by routing drain events to larger sloughs less prone to developing water quality problems. The rationale behind this BMP is that the smaller, dead-end sloughs have less assimilative capacity and less tidal mixing and thus are most susceptible to wetland discharges, while larger sloughs with their greater water volumes and higher tidal exchanges should have greater dilution capacity to help accommodate wetland discharges. For wetlands that do not have water control structures on larger sloughs, this BMP would require pipes, pumps and other infrastructure to implement. This practice has been used in the field but has not been subject to evaluation. Results of this study suggest its adverse effects via increasing net upstream flow in the smaller tidal sloughs outweighs its potential benefits of diluting discharges directly into the larger tidal sloughs.

Evaluation Summary

This approach is anticipated to have two effects. First, it would reduce wetland load discharges into the smaller Peytonia, Boynton, and other problem sloughs, which should improve their water quality. Second but working to opposite effect, it would increase reverse flows on these sloughs due to reducing the magnitude of ebb tide flows. The resulting reduced tidal mixing in these sloughs would increase residence times which, if high organic carbon levels are present such as from wetland discharges that could not be rerouted, would facilitate low DO conditions. This latter outcome would be avoided only if no wetlands or other sources of BOD or low DO discharged onto the slough. Therefore, the water quality benefits may be gained only through rerouting discharges from all wetlands along a particular slough, which in most cases would pose considerable infrastructure costs and coordination, and ensuring other possible BOD and low DO sources are also eliminated. Long term operations and management would increase and there could be environmental impacts from construction activities.

Further Study

On sloughs where it is feasible to implement for all wetlands so that there are no wetland discharges at all into the smaller sloughs, this BMP may be worth studying with focus on how increased upstream flows affect water quality. No further study recommended for sloughs where not feasible to implement for all wetlands. Use of hydrologic and hydrodynamic models would be useful to assess effects of proposed changes prior to their implementation.

Use Recommendation

First implement hydrologic model to quantify effects on slough flow directions, magnitude and hydraulic residence times. If modeling results indicate a beneficial effect, then consider using this BMP only where can achieve rerouting of all wetlands and undertake only with associated evaluation.

BMP H-7. Stagger Flood/Drain Events across Multiple Wetlands

Description

This BMP involves staggering over time the flooding and draining of multiple wetlands connected to each slough that has a history of poor water quality. The rationale behind this BMP is that (1) reducing the number of wetlands flooding at any one time will reduce the magnitude of net-upstream flow in the sloughs and (2) reducing the number of wetlands draining at any one time will reduce the magnitude of water quality impacts in the receiving sloughs. Implementation of this BMP would require close coordination between SRCD and all wetlands on affected sloughs. This BMP has not been tested in the field.

Evaluation Summary

This BMP would be expected to improve water quality conditions within individual sloughs due to the combined effects of increasing tidal mixing at the tidal cycle time scale (by reducing net upstream flows that concurrent wetland flooding induces) and reducing the concurrent discharges from wetlands and the associated loadings of low DO, high BOD, and elevated methylmercury. In effect, the BMP is a ‘temporal’ dilution approach. Effects on wetland management could be complex due to a shortened time period for initial flood-up management for those wetlands flooded later. Wetland management would have to be coordinated closely and landowners would have to be willing to make management adjustments to support overall water quality improvements.

Further Study

A trial of this method on one or two sloughs experiencing water quality problems is recommended to determine feasibility of implementation and water quality benefits. Modeling of the system could also be useful for predicting potential outcomes. In order to be effective, every wetland flooding or draining to the sloughs being studied would have to participate (i.e., requires willing landowners at every wetland connected hydrology to the slough).

Use Recommendation

Potentially useful.

BMP H-8. Coordinate Drain Events across Multiple Wetlands Using DO-Based Discharge Scheduling

Description

This BMP involves using real-time DO data collected within problematic sloughs to schedule wetland drain events across multiple wetlands connected to each problematic slough. The rationale behind this BMP is that by timing wetland discharges during periods of good water quality, the adverse impacts upon slough water quality of a given wetland discharge will be reduced. This BMP could be combined with BMP H-7 to improve discharge staggering among multiple wetlands. This BMP will require the installation and maintenance of water quality monitoring equipment as well as a system and personnel to monitor the real time data and communicate results and scheduling to wetland managers. This BMP has not been evaluated in the field.

Evaluation Summary

Timing wetland drain events across multiple wetlands according to DO conditions within the sloughs could reduce water quality problems within the receiving waters by tying discharge activities directly to real-time understanding of water quality conditions. The addition of this information service would provide wetland managers with flexibility in discharging and subsequent re-flooding for purposes of wetland management. However, the equipment and its operation and maintenance could be costly and the processes needed to disseminate information to wetland managers and ensure its use in wetland management could be complicated to set up and implement. Opportunities may be available to offset the costs and support implementation logistics of this program such as the USDA Environmental Quality Improvement Program (EQIP) grants.

Similar to BMP H-4, extended time periods of holding water within any wetland could have benefits for methylmercury (increased time for photodemethylation) and also detriments to wetland management (formation of black water conditions within the wetland.) This low quality water could impact wetland biota, decrease wetland productivity, cause a nuisance to landowners (black water, foul odors, etc.), make vector management more costly due to multiple treatments, and increase wetland salinity, potentially requiring additional salinity flood/drain events in the winter-spring.

Further Study

Additional study could be used to identify operational guidelines, constraints and strategies for implementing this BMP in a way that best accommodates other wetland management activities and goals. Management objectives may be combined with regional water quality efforts to help offset costs to wetland owners.

Use Recommendation

Has potential if wetland management coordination and significant cost issues (staffing and equipment maintenance) can be resolved. New funding sources such as USDA EQIP may be necessary to provide sufficient resources to cover costs and provide appropriate incentives for landowner participation.

BMP H-9. Maximize Use of Fairfield-Suisun Sewer District Treated Wastewater for Initial Flood-Up

Description

This BMP involves maximizing the use of FSSD water for initial flood up so as to minimize flooding from sloughs. The rationale behind this BMP is that reducing the amount of water drawn from the sloughs will reduce net upstream flows and consequently maintain better tidal mixing within the sloughs. This BMP is only applicable to wetlands that currently have or could reasonably achieve the necessary infrastructure to allow linkage to the FSSD discharges; currently, Wetlands 112, 122 and 123 have this connectivity. This BMP will require close coordination with FSSD staff. Ideally FSSD would provide slugs of water at certain times to flood wetlands. For instance, it would help to have FSSD store ~300 ac-ft for rapid flood up vs. current daily flows of about 30 ac-ft typically discharged down the pipe. Ability to store water at FSSD is dependent in part on rainfall storage needs. This BMP has not been field evaluated.

Evaluation Summary

FSSD primarily discharges to Boynton Slough but diverts some for use on Wetlands 112, 122, and123. During the fall, flows from the treatment plant are in the range of 16 – 19 cfs. The tertiary treated water has discharge requirements for DO and monthly averages in the fall are in the range of 6 – 7 mg/L. DOC and MeHg levels in this water are also low. This water could be preferentially used during the fall flood-up period to reduce the occurrence of low DO conditions. Directing more of the effluent onto the wetlands during flood-up would supply the wetlands with a better water source (higher DO, lower salinity, DOC, and MeHg) than the adjacent sloughs, while reducing the magnitude of net upstream slough flow during this time period. Following flood-up, the effluent stream could be redirected entirely into the sloughs to reduce net upstream flows and help flush wetland discharge water from the sloughs. This BMP would only be applicable to Wetlands 112, 122, and 123.

Maximizing use of this water during flood-up could help to reduce net-upstream flows in Boynton and Peytonia Sloughs and thus should help reduce the chronic DO problems. The magnitude of reduction in net upstream flow will be dependent on the flow rates that can be achieved from each discharge outfall. Relying more heavily on FSSD water will likely result in a longer time needed for flood-up, potentially increasing mosquito production and thus abatement costs. This BMP should be coupled with BMP H-10, below, which involves maximizing FSSD discharge into the sloughs during wetland discharge events.

Further Study

Additional studies are needed to assess the impact on reverse flow in the sloughs, determine impacts on wetland flood-up time and thus management needs, and to evaluate effectiveness at improving slough water quality.

Use Recommendation

Potentially useful. Discussions with FSSD would need to take place to discuss its participation; FSSD cooperated very effectively during conduct of this study.

BMP H-10. Maximize FSSD Discharges into Boynton and/or Peytonia Sloughs during Drain Events

Description

This BMP involves routing FSSD discharges into Boynton and/or Peytonia sloughs during times of wetland discharges, for the purposes of providing flushing flows and higher DO waters. This FSSD discharge routing would be accomplished through coordinated operations of FSSD discharge infrastructure with wetland managers and the associated wetland drainage activities. The rationale behind this BMP is that (1) the added FSSD outflows increase ebb tide flow rates and speed transport of wetland discharge water from the smaller sloughs into Suisun Slough, and (2) the relatively high quality of the FSSD discharge water (high DO, low BOD, etc.) will help to raise slough DO levels. Water from FSSD would preferentially be discharged to the sloughs after initial fall flood-up and should continue until early December, when water quality conditions within the sloughs generally improve. Water discharges could be directed to one or both sloughs at a time depending on management priorities. Depending on the nature of FSSD discharge infrastructure, this BMP could be tailored to discharge only on ebb tides which would allow maximum flood tide mixing up Peytonia and Boynton Sloughs. This fine-tuning is in essence a tidal pumping strategy hydrologically akin to winter operation of the Montezuma Slough Salinity Control Structure. This BMP has not been field-evaluated.

Evaluation Summary

Increasing upstream inputs into Boynton and/or Peytonia sloughs should have the effect of reducing net upstream flows and potentially promoting net downstream flows in these two sloughs. This change in flow regime is expected to result in reduced residence times and thus improved slough water quality for DO and MeHg. In addition, the introduction of high DO and low BOD waters into these sloughs should have the effect of diluting the low DO and high BOD wetland discharges. The results of this study indicate that Peytonia is generally the more impacted of the two sloughs and could potentially derive the greatest benefit from FSSD water. Preferentially directing the FSSD water into the sloughs would remove a source of fresh water from the wetlands, potentially making them more saline and require more salinity management flood/drain cycles in the winter/spring. If it is possible to provide a mixed approach that utilizes FSSD waters for wetlands and for direct slough discharges, then wetland management should be minimally affected. Cooperation of FSSD and coordination with wetland managers will be necessary for this BMP to be effective. This BMP would likely require modification of FSSD operations and probably increased cost to FSSD. ***Further Study*** Additional studies are required to determine (1) if the FSSD discharges are sufficient to improve DO levels in Boynton and Peytonia sloughs, (2) what the timing and magnitude of releases should be that would most benefit slough water quality, and (3) engineering assessment of infrastructure needs if any to support greater day-to-day management of FSSD discharge routing.

Use Recommendation

Potentially useful. Discussions with FSSD would need to take place to discuss its participation; FSSD cooperated very effectively during conduct of this study.

4.5.2 Water Management BMPs: Fall and Winter Circulation Period

BMP H-11. Minimize Exchange between Wetlands and Sloughs

Description

This BMP is similar to BMP H-4 in that it involves minimal exchange with the sloughs throughout the fall and winter water circulation period when water quality conditions within the sloughs are poor. The rationale behind this BMP is that reducing exchange between the wetlands and sloughs will isolate poor quality water within the wetlands when sloughs are most susceptible to impacts from wetland discharges. It should also allow for photodemethylation and microbial degradation of DOC to take place in wetland waters along with cooler air and water temperatures increasing DO saturation concentration and rainfall helping to mix waters and raise DO levels, thus lessening the impact of these constituents upon slough WQ when released. This BMP has not been evaluated in the field.

Evaluation Summary

This BMP will greatly reduce impacts of low-quality wetland water upon the sloughs during fall and winter water circulation operations. However, implementing this BMP may decrease wetland water quality over current conditions due to the reduction in exchange. If lower wetland water quality results, it could impact wetland biota, cause a nuisance to landowners (black water, foul odors, etc.), make vector management more costly, and increase wetland salinity, potentially requiring additional salinity flood/drain events in the winter-spring.

Further Study

This BMP requires additional feasibility evaluation to determine if it warrants field study. It has the potential to result in further increases in reduced soils conditions that could in turn promote additional mercury methylation; wetland soils are already fairly reduced following the fall flood-up cycle and this effect may be small. Additionally, this BMP may require the development of strategies to manage salinity, mosquitoes, and nuisances to landowners (black water, foul odors, etc.). If these challenges either do not exist in reality or can be overcome effectively through the development of sustainable strategies, reducing exchange rates may be a very effective strategy to improve water quality in the sloughs.

Use Recommendation

This BMP has the potential to interfere with wetland management objectives and increased costs. Therefore, its use would need to be considered carefully and its details worked out further than provided here. However, if its many challenges can be resolved then it has good potential to improve slough water quality conditions.

BMP H-12. High Exchange Rate between Sloughs and Wetlands

Description

This BMP is the opposite of BMP H-11 in that it involves a very high rate of circulation between the wetlands and adjacent sloughs. The rationale behind this BMP is that keeping a high rate of exchange will reduce the development of poor water quality conditions within the managed wetlands, thereby reducing impacts upon the receiving sloughs. The ability to implement this BMP will vary between wetlands based on their hydrologic conditions and abilities to flood and drain water efficiently. This BMP has been used by some wetlands in Suisun but has not been subject to evaluation.

Evaluation Summary

The ability to establish high exchange rates between sloughs and wetlands depends on the physical constraints and location of each wetland, the water control infrastructure of each wetland, the wetland elevations, tide stage, disturbance, cost, and time-of-year diversion restrictions (see Section 1.1.4). Additional water control structures and/or the use of pumps to drain lower elevation wetlands may be necessary and entail costs and possibly permit requirements. The effects on concentrations of DO, DOC, MeHg are not quantified though one wetland that has tried management approximating this BMP reports qualitatively improved water quality conditions as indicated by less blackwater events (Wetland 807; Jim Gaither, pers. comm.).

Results from this study, which were collected with typical wetland-slough hydrologic exchange rates, suggest that when conditions internal to the wetland produce low DO, high BOD, and high MeHg, more exchange leads to greater discharge and greater loading of these poor water quality conditions to the sloughs. The hypothesis underlying this BMP is that reduced residence times result in shortened time periods for microbial decomposition of organic matter within the wetland and thus less reduction in wetland water column DO levels. This hypothesis is predicated on residence time being the controlling process in microbial degradation; if, however, carbon pool size is the controlling factor and the wetland provides a sufficiently large carbon pool then a reduction in residence time may have no effect on reducing organic matter decomposition and the BMP would have the result of merely increasing loads into the tidal sloughs from the increased exchange rates.

Reduced residence times that this BMP would establish may reduce conditions that promote development of adverse water quality conditions. High chemical reaction rates and DOC diffusion rates, however, could increase BOD load to sloughs. Variations on this BMP would include selecting whether to flood and drain to or from large vs. small sloughs. Flooding from small sloughs would increase net upstream flows and thus if continue to have drains on these smaller sloughs from other wetlands could exacerbate poor water quality conditions in the slough, though this effect may be reduced somewhat by the increase in flow into the smaller sloughs that the increased exchange rates would generate.

Further Study

Data for this recommendation is very preliminary. Further study is recommended. Understanding the organic carbon reaction rates and capacity and the overall reaction kinetics would be helpful in understanding how effective high exchange rates would be for reducing water quality impacts, and for understanding the increase in loading that could occur from this approach.

Use Recommendation

May require financial and possibly regulatory compliance support to implement. Could require infrastructure upgrades to implement. Time-of-year diversion restrictions set inherent limitations. Lends itself to pilot study coupling wetlands operations with close water quality and process monitoring.

BMP H-13. Maximize Internal Wetlands Circulation

Description

This BMP focuses on maximizing internal circulation through improvements to ditches, swales, water control structures, and vegetation management so as to eliminate stagnant areas within the wetlands. The rationale behind this BMP is that improving internal circulation will improve hydrologic mixing within the wetlands and reduce the occurrence of poor water quality hotspots, thereby improving overall internal water quality conditions and therefore reducing the discharge of poor water quality into the sloughs. Improved internal circulation may therefore reduce the need for external exchange. This BMP has not been evaluated in the field though some wetlands have implemented circulation improvement measures. This BMP may be especially effective when combined with BMP H-12.

Evaluation Summary

Higher residence times support conditions that facilitate water column respiration and thereby reduce DO levels and allow for mercury methylation. The intent of improving internal circulation, therefore, is to generate more uniform residence times and thus reduce locations or hotspots of low DO and MeHg generation. This BMP itself would not increase oxygenation of water within the wetland unless the circulation infrastructure was specifically designed to do so. This BMP could have a relatively high cost because it will require construction and/or modification of ditches, swales, and other internal water control infrastructure. Effectively increasing mixing throughout a wetland is an easy concept to understand but very difficult to achieve because of preferential flow paths created by differences in vegetation density, water elevation, topography and ditches and drains that channel water flow. Consequently, careful design of circulation improvements would be essential. As described in BMP H-6, some matching funds for structural improvements may be available from the Federal EQIP program.

Further Study

An understanding of the economics to improve circulation through changes in infrastructure and management would be helpful as a starting point for this approach. Field tracer studies which can quantify the residence times in relation to water quality would be a good first step in understanding the potential.

Use Recommendation

Needs further investigation.

4.5.3 Water Management BMPs: Spring and Summer Salinity and Vegetation Management Period

BMP H-14. Summer Irrigation without Discharge

Description

This BMP involves one or more soils wetting cycles in the summer without discharge to sloughs. This BMP would take place following dry-land wetland management activities. The rationale behind this BMP is that periodic flooding of the wetlands will compact soils after management disturbance and promote biogeochemical degradation of labile and high BOD organic carbon before the fall flood-up period, thereby removing this carbon from being available when fall flood up takes place. This BMP would presumably be accomplished by operating water control structures to allow flooding to soil saturation levels. Alternatively (yet more costly) would be to operate a sprinkler system or another such approach that creates moist soil conditions. The BMP would be implemented as soon as possible after soil/vegetation management takes. Each cycle would allow two weeks for labile organic carbon breakdown. This BMP has not been evaluated in the field.

Evaluation Summary

This BMP could facilitate the breakdown of organic matter prior to the fall flood-up season and thereby improve water quality conditions. Three factors could complicate implementation of this BMP: (1) if accomplished by flooding via water control structures, could increase mosquito production which could require chemical treatment; (2) limits the available time for wetland managers to have dry soil conditions for wetlands management activities; (3) could promote weed growth which would be detrimental to wetland conditions, and (4) could increase soil salinities if carried out with more saline slough water as the irrigation source. In addition, if accomplished by operating water control structures, this BMP would slightly increase net upstream flow in sloughs due to diverting water into wetlands without any associated return flows. Use of a sprinkler irrigation approach with freshwater would alleviate many concerns but would be more costly.

Further Study

Additional study on this BMP could be used to set up operational protocols and guidelines for its implementation, recommend appropriate infrastructure, and identify the period before fall flooding for which no additional irrigation would be allowed. This additional study could be based entirely on feasibility studies and a literature review.

Use Recommendation

Potentially useful. This BMP may be the most effective strategy to remove labile organic carbon from the managed wetlands prior to fall flood-up and thus may have a high efficacy factor for improving water quality.

4.5.4 Vegetation and Soils Management BMPs

As discussed earlier in this document, within-wetland and between-wetland data suggest a land management effect on water quality constituents. The water quality data throughout the wetlands have high variance and so this determination is based mainly upon temporal trends. Other studies on conservation tillage and other land management practices strongly support the hypotheses that (1) land practices will affect BOD exports and (2) timing of management implementation can be used to minimize the BOD loading. The general theme of all the vegetation and soil management BMPs is to reduce the availability of labile organic carbon, which can originate from annual plant growth as well as soil carbon pools. Reducing loss of soil organic carbon pools would have the added benefit of reducing land subsidence.

BMP VS- 1. Manage for Less Leafy Green Vegetation

Description

This BMP involves managing the wetlands and seasonal water applications to promote non broadleaf wetland plants such as Watergrass (*Echinochloa* spp.), Japanese Millet (*Echinochloa* spp.) and Swamp Timothy *(Crypsis schoenoides)*. This can be achieved with a combination of management methods, proper water management and selective spraying of herbicides that select for broad leaf plants to further reduce broad leaf plant production. Promoting the growth of wetland grasses instead of broad leaf wetland plants for example Fat Hen *(Atriplex triangularis)* and Lamb's Quarters *(Chenopodium album)* and the control of Cocklebur (*Xanthuim strumarium*) and Annual Sunflower (*Helianthus annuus*) will produce less organic material and should in turn reduce the overall volume of vegetative matter and BOD load to the wetlands and subsequent impacts upon the adjacent receiving water bodies.

Evaluation Summary

This BMP is expected to reduce DOC exports and thus increase DO concentrations in the sloughs during the fall period and to reduce MeHg concentrations. There are several factors with this BMP that would need to be evaluated so the correct balance of soil disturbance, seasonal irrigations, and herbicide treatment is achieved. In order to grow grasses some discing and summer irrigations are needed, with these summer irrigations there is the potential for mosquito production which may require abatement treatments. A modification of BMP H-9 would allow irrigations to take place during the summer, without causing a net upstream flow in sloughs due to diverting water into wetlands. Additionally, irrigations require significantly less water than a fall flood event, thus reducing the net volume of water returned to the adjacent slough during draining of the pond post irrigation. Using FSSD water for irrigations would also help decrease withdraws from the sloughs and reduces soil salinities in the wetland soil creating a better environment for the targeted wetland grasses to grow successfully.

Further Study

Pilot studies utilizing this management technique are needed to identify the magnitude of the impact of this BMP, annual cost associated with required annual planting, seed bed preparation, herbicide treatments to better integrate it with other BMPs, and coordination with mosquito control.

Use Recommendation

Potentially useful.

BMP VS-2. Mow Vegetation Earlier in the Season

Description

This BMP involves vegetation mowing earlier in the summer than under current management practices. The rationale behind this BMP is that mowing earlier in the season will allow a longer period of time for the organic material to break down before fall flood-up, thus reducing the BOD load to the wetlands and subsequent impacts upon the adjacent receiving water bodies. As vegetation decomposition occurs predominantly under saturated soils conditions, this BMP is likely to be an effective strategy only in combination with either early field saturation (BMP H-14) and especially if mowed vegetation is mulched to speed its decomposition or removed altogether (BMP VS-3). This BMP has not been evaluated in the field.

Evaluation Summary

This BMP is expected to reduce DOC exports and thus increase DO concentrations in the sloughs during the fall period and to reduce MeHg concentrations. The magnitude of its effect is not clear as data from this study suggest land management effects are primarily associated with early flood-drain periods during the first few weeks to a month of the fall flood season. Also, this study has a high variance associated with the DOC data suggesting that a wide range of factors, not clearly understood, affect DOC and BOD sources and sinks. Thus, this BMP is expected to improve water quality but its absolute impact is unclear. From a wetland management standpoint, this BMP could result in multiple mowing events if mowing is conducted before the end of growing season and in reducing wetland productivity which may be counter to supporting wintering waterfowl.

Further Study

Pilot studies utilizing this management technique are needed to identify the magnitude of the impact of this BMP, to integrate it with other BMPs, and to examine the potential effects on waterfowl support.

Use Recommendation

Potentially useful when combined with other BMPs, pending results of pilot studies.

BMP VS-3. Remove Mowed Vegetation from Wetlands

Description

This BMP involves mowing the wetlands as under current management practices, but also involves baling the mowed material and hauling it off- site for disposal. The rationale behind this BMP is that removing the mowed vegetation will remove a major source of labile carbon and thus reduce BOD and subsequent low DO events in wetlands following fall flood-up. As with grazing (see BMP V-4), the benefit of this practice is that it physically removes the dead organic matter from the system (above-ground biomass but not the below-ground root system biomass) as opposed to leaving it within the wetland to be broken down by microbial activity, as is the case with mowing alone. This BMP has not been evaluated in the field.

Evaluation Summary

This BMP is anticipated to reduce low DO and elevated MeHg problems within managed wetlands as it involves directly removing a contributing source to the problem. This method may have issues with implementation as many managed wetland soils may be too soft to allow operation of heavy baling equipment; a range of equipment should be evaluated to determine what may be effective in soft soil conditions. It also may be expensive (equipment and labor) and baled material would have to be disposed (it could be composted). Baling would remove seed heads along with vegetative material reducing the food value of habitat.

Further Study

Pilot studies of this BMP should be conducted in managed wetland sites with suitable soils to assess feasibility in terms of ease of implementation, cost, and effect on low DO/ MeHg production.

Use Recommendation

If cost effective and feasible, this method could reduce organic carbon inputs to the wetland system, alongside late summer field wetting (BMP H-14).

BMP VS- 4. Graze Wetlands to Remove Unwanted Vegetation

Description

Under this BMP, grazing would replace mowing and herbicide application as the method for removing unwanted vegetation from the wetlands during the summer dry-land management period. The rationale behind this BMP is that plant consumption by grazing will remove a major source of labile carbon from the system and thus reduce BOD and subsequent low DO events in wetlands following fall flood-up. The benefit of grazing is that it actually removes organic matter from the system as opposed to leaving it within the wetland to be broken down by microbial activity, as is the case with herbicide and mowing treatments. This BMP has been evaluated in other systems, but not within Suisun Marsh.

Evaluation Summary

Grazing has been used throughout California to control weeds and manage vegetation communities. Experiments conducted by the Moss Landing Marine Lab on the Yolo Bypass have indicated that vegetation removal through grazing helps to reduce MeHg loads to surrounding water bodies. In wetland management, the main concern with grazing is that animals could consume the plant seeds that make for quality waterfowl forage once the wetlands are flooded. The results of the MLML studies indicate that seed production is still adequate so long as cattle are not left on the area too long. Sheep and goats are not preferred as they tend to remove seeds. Several questions are associated with grazing including: (1) does grazing reduce seed production or disbursement of preferred vegetation? (2) What type of livestock is best suited for grazing? (3) For which livestock is predation an issue? (4) Will certain livestock such as cattle have footing issues or damage the wetland sloughs through trampling? (5) What is the contribution of cattle waste (i.e., manure) to DOC and other water quality constituents of concern?

Further Study

This BMP is the most logistically complicated of the vegetation and soil management BMPs. Further evaluation of the logistics and potential benefits and problems associated with cattle, sheep, and goats would need to be undertaken to assess feasibility before any field pilot studies were undertaken.

Use Recommendation

Following further feasibility assessment, a pilot study may be warranted.

BMP VS- 5. Reduce Soil Disturbance (Discing) Activities

Description

This BMP involves reducing or eliminating the use of discing to control vegetation in managed wetlands. The primary purpose of discing is to set back plant succession to maintain selected productivity regimes deemed beneficial for wildlife use and waterfowl in particular. This method of vegetation management increases the availability of soil organic carbon that contributes to the low DO and MeHg problems and it promotes land subsidence. The rationale behind this BMP is that reducing or eliminating discing will reduce the amount of soil organic carbon that is made available to the water column within the wetlands. Two approaches are available for reducing these soil disturbances while meeting wetland management objectives: (1) replace discing with **herbicide control** (which has its own potential problems) or (2) employing **conservation tillage** practices from agriculture that seek to reduce the extent of soil disturbance relative to traditional discing. This BMP has not been evaluated in the field.

Evaluation Summary

The results of this study indicate that the DOC within the managed wetlands during fall flood-up is highly labile and primarily derived from dead/decaying organic matter with high humic compound content. Recently disturbed wetlands soils with high organic matter content can be a source for this type of DOC. By eliminating, reducing or applying appropriate conservation tillage discing practices for vegetation control, a major source for this highly labile DOC within the wetlands can be greatly reduced.

Further Study

Further study is recommended to determine the effect of reduced or eliminated tillage on DOC content and composition within managed wetlands and how to integrate with wetland management.

Use Recommendation

Potentially useful. To the extent that soil discing is a significant contributor to the labile organic carbon pool at time of fall flood-up, this BMP could have a demonstrable improvement in water quality conditions. It may be especially effective when applied in combination with late summer field saturation (BMP H-14) and potentially also mowing and removing vegetation (BMP VS-3).

Table 6. Best Management Practices Overview and Recommendations for Further Study and Evaluation

BMP No.	Description	Intended outcomes	Field Tried	Evaluation Criteria: Slough Water quality DO	DOC	MeHg	Upstr Slough Flow	Wet Mgmt	Discussion	Further Study	Avoid Use
Key to Outcomes Ratings											
	Desired			↑	↓	↓	↓	Help		Yes	
	Intermediate			NC	NC	NC	NC	Neut.		Maybe	
	Undesired			↓	↑	↑	↑	Hinder		No	Yes
Water Management-Based BMPs: Baseline											
	Baseline: flood and circulate	Business as usual	NA	NC	NC	NC	NC	Neut.	Existing practices	No	Yes
Water Management-Based BMPs: Initial Fall Flood-Up Period											
H-1	Pre-flood to shoot level, drain, immediate reflood	Used in 2007 at 112 and 123	Yes	↓	↑	NC	↑	Neut.	High 'first flush' pulse of DOC into sloughs reduces DO. Neutral on MeHg prod? Neutral or improve wetland WQ.	No	Yes
H-2	Pre-flood to field saturation level, drain, delayed reflood	Used in 2008 at 112 and 123	Yes	↓	↑	NC	↑	Neut.	Allows time to offgas decomposing organic matter relative to H-1	No	Yes
H-3	Pre-flood to field saturation level, drain, immediate reflood	Used in 2000s at some locations in attempt to reduce low DO	Yes	↓	↑	NC	↑	Neut.	Lower pre-flood stage may reduce DOC pulse quantity relative to H-1	No	Yes
H-4	Flood and hold with minimal exchange	Avoid poor WQ dsicharges to sloughs during sensitive periods (fall)	No	↑	↓	?	NC	Hinder	Reduces slough loadings from wetland 'first flush' low DO/high DOC waters and reduces circulation during fall when wetland WQ is poorest. Mercury effect unclear. Will produce "blackwater" nuisance to hunters and complicate vector control.	Maybe	
H-5	Delay flood-up as late as possible before hunt season	Initial flood up occurs with cooler temps	Ltd	↑	↓	↓	↓	Hinder	May compress time when wetlands flood up, spiking upstream slough flows; would require mgmt integration across wetlands.	Maybe	
H-6	Reroute wetland drain events	Reduce BOD loading to	Yes	↑?	↓	NC	↑	Neut.	Increased net upstream slough	Maybe	Yes

Table 6. Best Management Practices Overview and Recommendations for Further Study and Evaluation

BMP No.	Description	Intended outcomes	Field Tried	Evaluation Criteria: Slough Water quality DO	DOC	MeHg	Upstr Slough Flow	Wet Mgmt	Discussion	Further Study	Avoid Use
	to large sloughs	sloughs with lower DO capacity							flows reduce mixing which promotes low DO in sloughs; **model before try further**		
H-7	Stagger flood/drain events across multiple wetlands	Spread out WQ and hydrologic effects temporally	No	↑	↓	↓	?	Neut?	Requires multi-party coordination; effects on wetland management may be complex	Yes	
H-8	Coordinate drain events across multiple wetlands using DO-based discharge scheduling	Base operational decisions on real-time data of slough water quality	No	↑	↓	↓	NC	Hinder	May complicate vector control and wetland management but potential water quality improvements could be	Yes	
H-9	Maximize use of FSSD water for initial flood up	Provide higher DO wetland inflows, reduce upstream slough flows	No	↑	↓	NC	↓	Neut.	Requires FSSD active participation and coordination, maybe infrastructure changes	Yes	
H-10	Maximize FSSD water discharge into Boynton and/or Peytonia sloughs during drain events	Dilute low DO/high DOC water in Boynton Slough; minimize net upstream flow	No	↑	↓	↓	↓	Neut?	Requires FSSD active participation and coordination, maybe infrastructure changes; may have wetland salinity effects	Yes	
Water Management-Based BMPs: Circulation period (winter, hunting season)											
H-11	Minimum exchange between wetlands and sloughs	Avoid poor WQ discharges, allow photo-demethylation and wind mixing	No	↑	↓	↓	NC	Hinder	Reduced slough loadings. Likely to create poor wetland conditions including blackwater (low DO within wetland)	Maybe	
H-12	High exchange rates	Minimize residence time in wetlands to avoid development of poor water quality	Ltd	↑	↑?	↓	Vary	Help	High DOC diffusion could increase BOD load, perhaps offset by high dilution rates. May require pumps to achieve circulation rates. Could increase upstream flows. May worsen conditions due to high DOC loading rates	Maybe	
H-13	Maximize internal wetland circulation	Eliminate stagnant areas	Yes	↑	?	↓	NC	Help	Requires physical improvements to internal circulation infrastructure that may prove difficult to achieve	Maybe	

Table 6. Best Management Practices Overview and Recommendations for Further Study and Evaluation

BMP No.	Description	Intended outcomes	Field Tried	Evaluation Criteria: Slough Water quality DO	DOC	MeHg	Upstr Slough Flow	Wet Mgmt	Discussion	Further Study	Avoid Use
Water Management-Based BMPs: Salinity and vegetation management period (spring and summer)											
H-14	Summer irrigation, no drainage	Compact soils, accelerate labile organic decomposition	Ltd?	↑	↓	↓	↑	Hinder	Potential challenges of mosquito production, diversion limitations, weed growth, and reduced time for wetland management	Maybe	
Vegetation and Soil Management-Based BMPs											
VS-1	Manage for less leafy green vegetation	Reduce labile organic matter	Yes	↑	↓	↓	NC	Help	Important practice	Yes	
VS-2	Mow vegetation earlier in the Season	Allow longer vegetation decomposition period	No	↑	↓	↓	NC	Neut?	Decomp mostly requires wetting which may complicate mgmt.	Yes	
VS-3	Remove mowed vegetation from wetlands	Reduce labile organic matter from dead vegetation	No	↑	↓	↓	NC	Neut?	Ability may depend on wetland soils ability to support baler (may not work on peat soils)	Yes	
VS-4	Graze wetlands to remove unwanted vegetation	Reduce labile organic matter from dead vegetation	No	↑	↓	↓	NC	Neut?	Yolo Bypass shown benefits. May be logistically challenging. Integrate w/ veg mgmt.	Maybe	
VS-5	Reduce soil disturbance (disking) activities	Reduce soil organic matter content available for decomposition	No	↑	↓	↓	NC	Hinder	Could be key strategy to reduce main carbon pool that contributes to water qualit problems; may complicate site management	Yes	

5 Study Limitations and Associated Uncertainties

This study accomplished a considerable amount in improving our understanding of low DO and high MeHg loadings in the northwest Suisun Marsh and in identifying a suite of possible best management practices that may help to alleviate these poor water quality conditions. Below we list key sources of uncertainty that limit our ability to draw definitive conclusions.

5.1 Confounding Data

One of the major uncertainties with the current dataset is how to distinguish between hydrologic and land management effects on water quality characteristics. The studied wetlands are different in their configuration (e.g., elevation, water supply availability) and management (e.g., land preparation practices, hydrologic management). These differences between wetlands complicate the interpretation of trends and the evaluation of (confounding) data. To overcome this problem, replicates and small scale targeted studies should be used. These practices were not able to be done in this study so data interpretation is a blend of interpretation of trends and statistics, and extrapolating from other studies. This approach has its limits.

5.2 Short Timeframe

The timeframe for this study is very short with only about 15 months of field data to capture two fall periods and one winter period. Though the data coverage during this time period is extensive, the short duration does not allow for longer term climatic effects to be uncovered nor to isolate wetland management actions as concretely as necessary for decision making.

The findings in this report are based on high frequency data that is ultimately time averaged to uncover general non-tidal, seasonal and annual patterns. Constituent monitoring including flow, salinity, temperature, and DO, allowed estimation of material loading rates that explain trends in constituent accumulation. There are also clear differences between the sloughs that appear to reflect relative position and land use. While our methods are well tested, flux estimation requires very high measurement precision in the high-frequency domain to assure accuracy of filtered results – the classic signal to noise problem. All reported flux estimates have a mechanistic basis and therefore engender confidence in their veracity. Future flux estimation should verify magnitudes of system response.

5.3 External Contribution Uncertainties

This study focused on water quality characteristics within the managed wetlands and their adjacent sloughs. We did not investigate the contribution of other potential sources to the low DO and MeHg problems within northern Suisun Marsh. The most potentially significant contributing sources to these problematic events are input from the surrounding watershed and inputs from managed wetlands connected hydrologically to Peytonia or Boynton sloughs but not included in the study. The Suisun Marsh watershed contains agricultural, urban, and open space land cover classes, which can contribute water with elevated DOC, BOD, and nutrient concentrations. Though nutrient concentrations within the wetlands and sloughs were not studied in this effort, they can be significant contributors to the low DO problem by stimulating primary production (algae and vegetation) within the water column. The breakdown of this additional organic matter by microbial respiration will contribute to the overall reduction in DO levels within the water body.

The land uses in the Suisun watershed and compliance with any regulations pertaining to the water quality effects of these land uses determine the type and quantity of nutrients and organic carbon loading into Suisun Marsh. This study did not examine the specific operational conditions or water quality discharges from any of these lands uses. Therefore, here we list some possible contributors and recognize that review of existing information may determine whether any can be eliminated from further consideration or identified as in need of further examination. **Table 7** lists the land cover types the Suisun watershed and **Figure 3** shows their locations. Each land cover type has varying capacities to contribute to nutrient and OC loading into Suisun Marsh. Urban land uses in Fairfield, Suisun City and Travis Air Force Base could contribute to the nutrient load of Suisun Marsh through stormwater and irrigation runoff containing landscaping fertilizers, detritus, and the like. Stormwater from creeks and outfalls enters Suisun Marsh untreated. Consequently, loadings from urban runoff are fairly likely to occur though this study did not seek to identify data availability to quantify this contribution. The Fairfield-Suisun Sewer District treatment plant is authorized to discharge nutrients into Suisun Marsh to NPDES permit levels (

Table 2 presents those levels). Irrigated perennials and annuals could contribute nutrients from fertilizers through irrigation water runoff and stormwater runoff. Dairy and pasture lands are potentially fertilized and thus could contribute nutrients through stormwater runoff and, if irrigated, through irrigation water runoff. The number of livestock on dairy and pasture lands and the management details of each operation would determine the amount of nutrients, if any, entering Suisun Marsh. However, regardless of the number of animals, nutrients from livestock manure could enter the marsh through stormwater runoff and through the washing of milking parlor floors. If not sequestered in accordance with water quality requirements for these operations, this wash water could runoff into the marsh. Non-irrigated crops, predominantly made up of dry-farmed oat hay, could contribute nutrients mainly during storm events when fertilizers are washed from the fields into the marsh. Farmsteads (include farmsteads with and without a farm residence) and fallow and idle land (land not cropped the current or previous crop season, but cropped within the past three years; or new lands being prepared for crop production) could contribute nutrients predominantly through stormwater runoff. Even though fertilizer may not be applied to fallow or idle fields, the nutrients accumulated in the soil from previous seasons of cropping could continue to be carried into the marsh via stormwater. Parcels categorized as native vegetation have the potential to contribute nutrients to the marsh if the land is grazed by livestock. The nutrients in livestock manure could enter the marsh through stormwater runoff. Ungrazed native vegetation parcels might contribute an insignificant amount of nutrients into the marsh system through the breakdown of organic matter that enters the system through stormwater runoff. Organic carbon can come from many of these sources and it is more likely to be in particulate form such as plant detritus.

Table 7. Land Use Distribution within the Suisun Marsh Watershed

Land Use Type	Acres
Irrigated Perennials	5,519
Irrigated Annuals	3,410
Dairy & Pasture	283
Mixture of Agriculture, Urban, Native Vegetation	837
Non-Irrigated Crops	8,685
Farmstead, Fallow and Idle	2,938
Mixture of Urban and Native Classes	4,706
Native Vegetation	243,927
Urban	109,618
Water	37,110
Total acres	**417,033**

** See **Figure 3** for geographic distribution of these land uses*

6 Recommendations for Further Actions and Studies

Based on the findings of this study, consideration of factors this study did not address, and the development and evaluation of the BMPs, we have identified a number of further actions and studies intended to address key uncertainties and advance our understanding and most importantly our ability to achieve reductions in adverse water quality conditions in Suisun Marsh.

6.1 Rigorous Field Testing of Viable BMPs

The first and most obvious recommendation is that further field testing of viable BMPs should be undertaken in the framework of a rigorous scientific evaluation and should last over enough management seasons and involve as many wetlands as possible so as to help separate out factors affecting variability in results. The processes that drive low DO and high MeHg are many and complex and they originate both within individual wetlands and from external conditions, making for a challenging scientific investigation. Yet it is important that efficacy be established with scientific rigor so that future management strategies are based on best available knowledge.

6.2 Investigate Watershed Contributions

As described above in Section 6.1.3, the Suisun Marsh watershed may contribute significant quantities of nutrients, DOC, and BOD to the marsh, contributing to low DO and elevated MeHg events. It is important to understand the relative contribution of these sources to develop a comprehensive strategy for reducing the occurrence and severity of such events. We would propose a two-phased approach: data mining/literature review and if necessary new field investigations. Data mining and literature review could provide significant and cost effective benefits to understanding the watershed and could also help with defining an appropriate sampling /monitoring plan for Suisun. If first-phase findings indicate a need for new field data, we would propose implementing a study based on those findings to investigate the water quantity and quality entering the marsh from the surrounding watershed throughout the year to determine how these events may contribute to low Do and elevated MeHg events.

6.3 Review Regulatory Standards

The current regulatory standard for DO in Suisun Marsh, as established in the Basin Plan for San Francisco Bay (RWQCB 2007), is 7.0 mg/l with the three-month median DO concentration not less than 80% of the DO concentration at saturation. The appropriateness of this standard and the ability for it to be met under current Suisun Marsh conditions should be analyzed in light of the results of this study. Clearly, the sloughs have difficulty meeting the regulatory requirements for DO. From mid-September through early December and from early April into the summer, DO is generally below 7 mg/L. If this entire period does not represent a period in which fish are at risk, then perhaps the standard is too high and should be revisited.

As a rule, the 7 mg/l water quality standard works well for fish, because all species can feed, grow, and function in various ways with few inhibitions, provided temperatures are also adequate, and 7 mg/l is not too far below saturation at lower temperatures. Tidal marshes under natural conditions are capable of producing lower DO levels, driven by decomposition of their high productivity. Native species that evolved with Suisun Marsh as a large-scale estuarine tidal marsh complex had adapted to these period lower DO conditions through a variety of strategies. As Suisun Marsh is being considered for large-scale tidal restoration, it is possible that an outcome of that restoration is contribution to low DO from those restored tidal marshes. It would not make great sense for Suisun to be considered out of compliance with water quality standards under these conditions. What is important is to make sure that with current wetland types in Suisun Marsh that native fish species have maximum access to aquatic habitats and their associated productivity and other ecosystem functions.

Thus, a more nuanced approach to the dissolved oxygen standard for Suisun Marsh may be appropriate that takes into account natural processes of tidal marshes and maintains addressing anthropogenic sources of poor water quality especially where they limit access to aquatic habitat and can lead to fish kill events.

6.4 Develop and Use Simple Wetland Hydrologic Models

One issue that became clear during the development and review of the BMPs is that few if any tools exist to critically evaluate a prospective managed wetland operational change. Some BMPs may prove very effective and others not so effective. Field testing BMPs can be costly and complicated to implement and thus moving forward with either pilot or large scale BMP efforts would best be done after more thorough vetting. As much of the BMPs in this study focus on hydrologic changes including integrating those changes with vegetation and soil management, we have identified that development of simple wetland hydrologic models would be extremely useful. Such models would be used to test the underlying hypotheses of each BMP and also to test assumptions about controlling processes and thus sensitivity to BMPs.

6.5 Implement Systematic DO Sampling in Peripheral Sloughs

A number of questions remain following this study, some newly raised by the findings and others existing that the study did not address in part or whole. Keeping in mind that the low DO issue applies to the peripheral sloughs along Suisun and Montezuma sloughs and more documented along Suisun Slough, the following questions should be pursued further. In undertaking any systematic sampling, we would recommend seeking to make as broad-based a program as possible that would support diked managed wetland operations, water quality improvements, and possible tidal marsh restoration. In other words, make efforts more integrative and comprehensive.

1) **What are the geographic boundaries of tidal sloughs subject to periodic low DO conditions?**
   Most of the existing periodic DO measurements come from the UCD Suisun Aquatic Monitoring program and thus the only systematic database on DO is roughly monthly at the UCD monitoring stations. Monitoring takes place on Montezuma, Suisun, Nurse, Denverton, Cutoff, First Mallard, Second Mallard, Peytonia, Boynton, and Goodyear sloughs (see locations in **Appendix D, Figure 2**). Notably absent from this long-term monitoring program are the tidal sloughs west of the railroad line, presumably due to the railroad interfering with boat access.

2) **What are the magnitudes and durations of low DO events?**
   Little long-duration, high frequency DO monitoring has occurred in Suisun Marsh. Without such data, neither the magnitudes, durations, nor full geographic extents of low DO conditions can be established. Given that at least some of the detection of low DO problems occurs only by the UC Davis monthly monitoring activities, the ability to have a more effective monitoring will help establish where, when, and why these problems occur and will contribute to their resolution.

3) **How can managed wetland operations be timed across multiple properties to yield water quality improvements?**

One BMP that may prove effective is to operate managed wetlands connected to those sloughs with known history of low DO problems with as much real-time water quality information as possible. Installation of a focused DO monitoring network would allow such operations to take place, if those operations are centrally coordinated such as by SRCD. This approach would require funding for its setup and operation.

6.6 Implement Systematic Methylmercury Evaluation of Managed Wetlands

Little data exist on the MeHg loadings from managed wetlands in Suisun Marsh. Most of the past MeHg studies in Suisun have been in the tidal systems. Prior to this study, only incidental sampling of managed wetland discharges occurred and with very few samples having been collected and analyzed. This study has the first data set for the managed wetlands and its sample size is ultimately very small and difficult to extrapolate from. A separate study, conducted informally, is providing information on MeHg at Blacklock following its restoration from diked marsh to tidal marsh. In other words, Suisun lacks an adequate baseline on MeHg contributions from diked, managed wetlands.

6.7 Economic Assessment of BMPs

This study does not assess the economics of any of the BMPs though it does identify those that may be more costly. We recommend that BMPs with technical merit for further consideration include an economic assessment. This assessment should examine costs for planning, regulatory compliance (if any), construction/initial establishment, long-term operations, and the necessary associated monitoring as part of its scientific assessment of efficacy. There may be a range of external funding sources that could be sought to cover part or all of such costs and matching the nature and outcomes of the BMPs helps to determine what funding sources may be appropriate to pursue.

6.8 Other Possible Actions

The last remaining topic to pursue are ‘other’ actions that are either external to the managed wetlands or are taking a very different approach to the managed wetlands. Here is a short list of what some of those actions could be; this list is not intended to be exhaustive.

Actions External to the Managed Wetlands

1) Convene a workshop comparing approaches to wetland management with other areas of the state/country and getting leading practitioners and academics together to talk about myth and facts.

Actions within the Managed Wetlands

1) Collect data on additional managed wetlands that link hydrologically to the sloughs with known low DO problems. Solving the problem on any particular slough is likely going to require addressing all lands that influence each slough.
2) Restoration to full tidal action through breaching of levees and other related activities. Selecting properties for this approach would require careful consideration of the hydrologic effects on the tidal sloughs to which the property is or could be connected. This approach is highly likely to reduce generation of low DO and high MeHg conditions. It does, of course, significantly change the nature of the land use. It also has the potential to affect tidal prism and salinity in the area of the breach.
3) Conversion to a ‘micro tidal’ marsh – redesign the levees and levee interior to allow higher spring tides to overtop and thereby provide a more frequent hydrologic inundation regime. This approach warrants evaluation through hydrologic models to understand its effects on water quality. This approach may cause mosquito production problems.

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Appendix A: Site Descriptions

A.1 Introduction

The bulk of the data collection and analyses in this project were focused in two managed wetlands, Suisun Farms (Club 112) and Walnut Creek Gun Club (Club 123), in northwest Suisun Marsh (Figure 1). More limited data collection also occurred in three managed wetlands, Balboa Farms (Club 525), Sprigsville Ranch (Club 529), and Bulrush Farms (Club 530), in central Suisun Marsh. All these wetlands are managed for waterfowl hunting by private landowners with assistance from the Suisun Resource Conservation District. The clubs are variable in size, ranging from 108 acres to 281 acres. This section describes the characteristics of each of these managed wetlands in terms of their existing physical and biological conditions as well as management practices.

A.2 Existing Conditions

The existing conditions of the five clubs in terms of topography, hydrology, soils, and vegetation are described in detail below. An overview of these general club characteristics can be found in Table 1. Club characteristic data is somewhat limited in the central clubs as these areas were not the primary focus of the investigation.

There are two distinct wetland basins in Club 112, the "hog patch", which is situated between the railroad tracks and an interior levee, and the main pond on the west side of this interior levee. There are also two distinct wetland basins in Club 123, the main wetland basin that encompasses most of the site and a smaller southern basin, which is separated from the main basin by a levee. The southern basin of Club 123 was not investigated in this study and therefore receives little treatment in the descriptions below.

A.2.1 Topography

California Waterfowl Association performed topographic surveys of Clubs 112 and 123 in the summer of 2007. These surveys covered the marsh plain and adjacent upland areas in the managed wetland portions of the properties. The perimeter borrow ditches were not covered in the survey.

Club 112

The topography of the managed wetland portion of Club 112 is displayed in Figure 2. The managed wetlands are surrounded by levees with elevations in excess of 8 ft NAVD. The topography within these basins represents channels, depressional ponds, and higher marsh plain areas. The mean marsh elevation in Club 112 is 4.79 ft NAVD88.

Club 123

The topography of the managed wetland portion of Club 123 is displayed in Figure 3. As in Club 112, the managed wetlands are surrounded by levees with elevations in excess of 8 ft NAVD88. The mean marsh plain elevation in Club 123 is 3.03 ft NAVD88.

Clubs 525, 529, 530
There are no data available for these managed wetlands.

A.2.2 Hydrology

Clubs 112 and 123 are located in northwest Suisun Marsh. The clubs are hydrologically connected to the adjacent sloughs via water control structures which allow wetland managers to regulate water levels within the clubs. Both clubs also receive an input of tertiary treated wastewater from the Fairfield-Suisun Wastewater Treatment Plant at a single outfall in each club.

Clubs 525, 529, and 530 are located in central Suisun Marsh. The clubs are hydrologically connected to a central water supply ditch that is connected to Montezuma slough via fish-screened water control structures. Water control structures between the clubs and the central supply ditch allow wetland managers to regulate water levels within the clubs. The hydrology of each club is described in detail below.

Club 112
The primary water supply for Club 112 comes from a small, man-made extension of Peytonia Slough, which is connected to Suisun Slough. The connection between the club and the slough is regulated via three water control structures (Figure 4). The hog patch is connected by one flood/ drain structure and one drain structure, while the main pond is connected via a single flood/drain structure. The main pond receives tertiary treated wastewater from the Fairfield-Suisun Wastewater Treatment Plant via a 13" pipe near the southwest corner of the Club. The amount of water received from this source is dependent upon the discharge from the wastewater treatment plant at any given time. The wetland managers have the ability to control how much of this water they allow into the club at any one time. There is also a small, 12" culvert at the northwest corner of the managed wetland that brings in rainfall runoff from the pastures at the northwest end of the Club property. The main pond and the hog patch are connected by two uni-directional water control structures that can transfer water from the main pond into the hog patch.

The water managers manipulate water levels and flow-through rates within the wetlands for a variety of purposes throughout the year (see Section 3, Club Management). During waterfowl season the water levels are held relatively constant at what is known as "shoot level". In Club 112, the water surface elevation (WSE) of shoot level is 5.5 – 6.0 ft NAVD88, which produces an average water depth of 0.71-1.21 ft across the club. This shoot level WSE translates into a storage volume of 78-133 ac-ft.

Club 123
The main wetland basin of Club 123 is connected to the surrounding Suisun Marsh system via six water control structures (Figure 4). There are two water control structures along Peytonia Slough, one along the man-made extension of Peytonia Slough, and three along Boynton Slough. There is also an input of tertiary treated wastewater from the Sewage Treatment Plant via a 24" pipe in the southwest corner of the club. AS in Club 112, the amount of water discharged from this pipe depends on the daily discharge from the treatment plant. The wetland managers have the ability to control how much of this water they allow into the club at any one time. The southern basin of Club 123 is connected to Boynton Slough

by a single water control structure and also receives tertiary treated wastewater via a 24" pipe. In Club 123 the WSE of shoot level is 4.0 – 4.5 ft, which produces an average depth of 0.97 – 1.47 ft across the club. This shoot level WSE translates into a storage volume of 223 – 337 ac-ft.

Club 525

The water supply for Club 525 comes from the man-made ditch (called fish screen supply ditch) that is connected to Montezuma Slough via fish screened water control structures. The connection between the club and the ditch is regulated via six water control structures (Figure 5). The club drains directly to Montezuma Slough via a 10" 15 hp electric pump. This pump is also used to provide circulation within the club.

The water manager maintains a constant year-round water level with minimal flow-through rates for the purpose of waterfowl brood habitat (see Section 3, Club Management).

Club 529

The water supply for Club 529 comes from the fish screen supply ditch that is connected to Montezuma Slough. The club takes water from Solano Cut portion of the supply ditch via two flashboard risers (a 24" pipe and a 12" pipe) (Figure 5). The club drains into an intermediate water body to the north called Frost Lake. Frost Lake then drains into Montezuma Slough. Frost Lake is not tidally influenced and has three drain structures into Montezuma Slough. Circulation and drainage on this club are limited by the slow drainage of Frost Lake to a water level low enough to enable drainage out of club 529. The landowner has control of their intake (mentioned above) in that they can regulate the water control structures in order to decrease the amount of water entering the club.

Club 530

The water supply for Club 530 comes from Solano Cut via the fish screen supply ditch that is connected to Montezuma Slough (Figure 5). The club takes water from Solano Cut via two 24" and one 18" canal gates. The club drains to the south into Poleline Ditch. Poleline Ditch is not tidally influenced and is pumped into Montezuma Slough. The landowner has control of their intake (mentioned above) in that they can adjust the two canal gates in order to decrease the amount of water entering the club.

A.2.3 Soils

The soils in Club 112 and 123 are remarkably different (Figure 6). The soils of Club 112 are more mineral in nature (primarily silty clay loam), while the soils in Club 123 are more organic (primarily peaty muck and mucky clay).

The soils in the central marsh clubs are also somewhat heterogeneous (Figure 7). Club 529 is entirely muck and silty clay, Club 525 is muck and silty clay with a large deposit of mucky clay in the center of the property, and Club 530 is muck and silty clay with a deposit of silty clay loam along the southern edge of the property.

A.2.4 Vegetation

The vegetation within Clubs 112 and 123 was surveyed in the summer of 2007 for this project. The vegetation within Clubs 112 and 123 is remarkably different (Figure 8, 9). Club 112 is dominated by saline wetland (51%) vegetation, while Club 123 is dominated by brackish wetland (37%) and freshwater wetland (52%) vegetation.

The vegetation within the central clubs was surveyed by CDFG in 2003 as part of a Suisun Marsh-wide vegetation monitoring program. The central clubs are dominated by saline wetland vegetation, with variable lesser quantities of brackish and freshwater wetland vegetation (Figure 10).

A.3 Club Management

Landowners in Suisun Marsh actively manage the vegetation community in their wetlands to achieve a beneficial food source for wetland dependant wildlife, manage for nuisance invasive vegetation, and reduce potential impacts to water quality. Management activities include both mechanical and water management techniques. Many of the vegetation management procedures are recommended by the SRCD to reduce the current low DO problems in Suisun Marsh and are outlined in “A Guide to Waterfowl Habitat Management in the Suisun Marsh” (Rollins, 1981), produced by CDFG.

Mechanical techniques primarily include mowing, disking, and herbicidal treatments, which are employed to reduce the presence of unwanted or invasive vegetation and reduce vegetative ground cover. Water management involves a series of flood-drain cycles timed throughout the year to reduce soil salinities, and encourage the establishment of a plant community that is beneficial to wetland dependant wildlife.

Maintaining low soil salinities in the managed wetlands is a high priority. If the soils become too salty, salt tolerant plants are encouraged to invade which provide less value to wildlife than fresh water wetland plants. While the wetlands are flooded for the migratory waterfowl use, water is circulated throughout the club to keep salinities as low as possible. In the winter and early spring, following waterfowl hunting season, a series of 2-3 flood-drain cycles are usually performed to flush accumulated salts from the soils, taking advantage of reduced water salinity in Suisun Marsh during that time of year. In the summer, the wetlands are normally drained for a period of 1-3 months so that landowners can perform other maintenance activities on the wetlands. This dry period also allows wetland plants to seed and sprout. The entire years work, leaching, circulating, mowing, disking, and other maintenance is done so that the wetland plants will provide food, in the form of seed, and cover not only for waterfowl and other wildlife but also for aquatic inverts which are also used as a food source.

The vegetation management activities in the various clubs are described below. A detailed schedule of the management activities in Club 112 and Club 123 is presented in Table 2.

A.3.1 Club 112

In Year-1, Club 112 used both mechanical and water management techniques to control the vegetation community in the wetland.

Mechanical

- -80 acres were mowed using a standard rotary deck mower to reduce the amount of vegetative material available for decomposition.
- - 25-acres of invasive cocklebur Xanthium spp. were sprayed when the managed wetlands were dry with herbicides to reduce the numbers of this species

Water Management

In February of 2007, following the close of waterfowl hunting season, the water managers drained the marsh plain of the club and then performed a series of three flood-drain cycles to leach salts from the soils. After the last leach, the water level was held at half of the normal (fall management level) height until April 15, when the entire club was drained. The water managers then performed two flood-drain irrigations per month in May and June after which point the club was drained for the remainder of the summer. On September 28 water was brought to slightly below fall managament level, then immediately drained and reflooded to a desired height for waterfowl season. Once flooded to desired height the water was circulated at the highest rate possible. For detailed water control structure height see Water control structure log book for 2007/2008.

In Year-2, mowing was done with a flail mower instead of a rotary deck mower and vector control spraying treatment was completed. Aside from this change all other management activities were identical to those in Year-1.

A.3.2 Club 123

In 2007 Club 123 also used both mechanical and water management techniques to manage the vegetation community in the wetland.

Mechanical

- 5 acres of the wetland were mowed using a standard rotary deck mower in August to reduce the amount of vegetative material available for decomposition.
- -60 acres of the wetland were disked in August to reduce the presence of broad-leafed vegetation
- -125 acres of invasive cocklebur were sprayed with herbicides when the managed wetlands were dry to reduce the numbers of this species

Water Management

In February of 2007, following the close of duck hunting season, the water managers drained the marsh plain of the club and then performed a series of three flood-drain cycles to leach salts from the soils. After the last leach, the water level held at half of the normal (fall management level) height until April 15, when the entire club was drained for the remainder of the summer. On September 15, 2007, water was brought to fall level or slightly below then immediately drained and reflooded to a desired height for waterfowl season. Once flooded to desired height the water was circulated at the highest rate possible. For detailed water control structure height see Water control structure log book for 2007/2008.

In Year-2 the following changes to management practices were made:

1) A flail-mower was used as opposed to a rotary deck mower
2) 120 ac of invasive cocklebur were treated with herbicides
3) The pre-flood period in September 2008 was followed by a 6-day drying period prior to full flood-up
4) Focused grading of the marsh plain to improve circulation and facilitate club drainage was performed in the southwestern corner of the main basin (near WCS 6)
5) Spray treatment of the ponds for the abatement of mosquitoes

All other management activities remained the same.

A.3.3 Club 525

In 2007, Club 525 was permanently flooded and therefore no mechanical techniques to control the vegetation community in the wetland were performed.

A.3.4 Club 529

In 2007, Club 529 used both mechanical and water management techniques to manage the vegetation community in the wetland.

Mechanical

- 10 acres of the wetland were mowed using a standard rotary deck mower in September to promote waterfowl use
- -2 acres of the wetland were disked in September to set back plant succession
- -7.5 acres of invasive common reed, *Phragmites* sp., were sprayed with herbicides to reduce the numbers of these species

Water Management

In April of 2008, the water manager drained the marsh plain of the club and then performed one flood-drain cycle to leach salts from the soils. After the leach, the water level was held at half of the normal (winter level) height until July 15, when the entire club was drained for the remainder of the summer. On October 1, 2007, water was brought to a desired height for waterfowl season. Once flooded to desired height the water was circulated at the highest rate possible.

A.3.5 Club 530

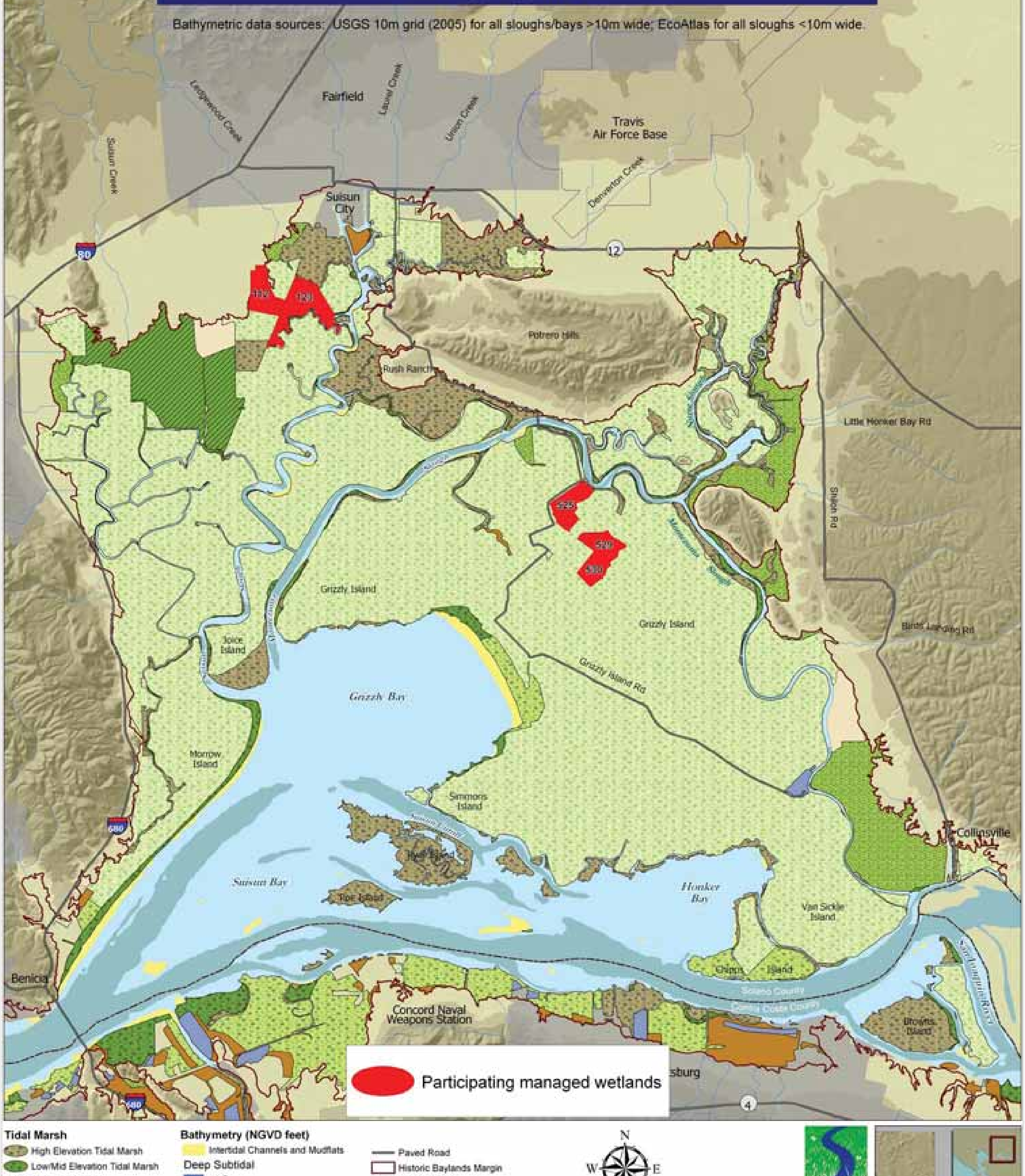
In 2007, Club 530 used only water management techniques to manage the vegetation community in the wetland.

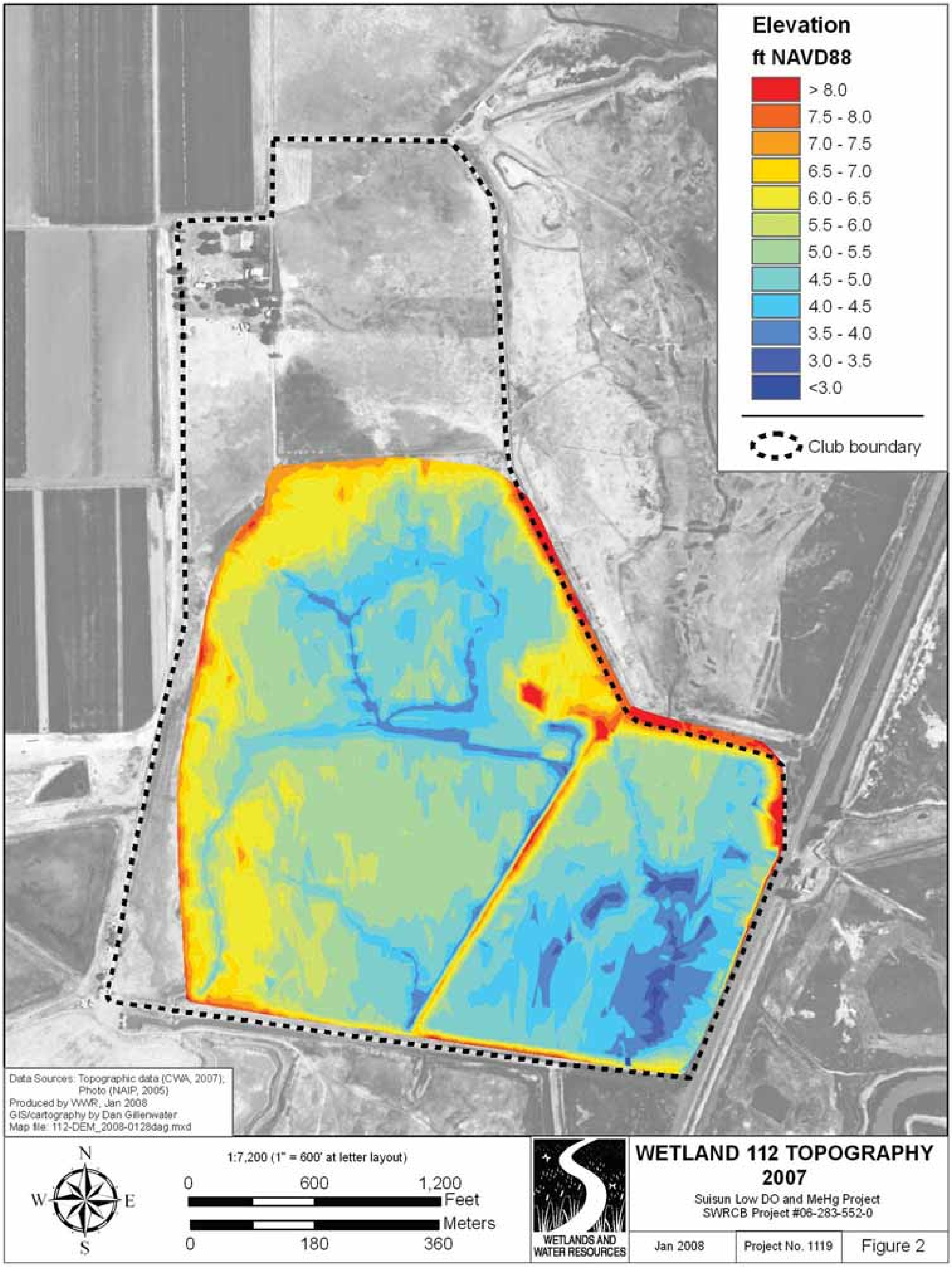
Water Management

In February of 2008, the water manager drained the marsh plain of the club. On October 1, 2008, water was brought to a desired height for waterfowl season. Once flooded to desired height the water was circulated at the highest rate possible.

Figures

Figure 1: Participating Managed Wetland Locations
Suisun Bay Region, California

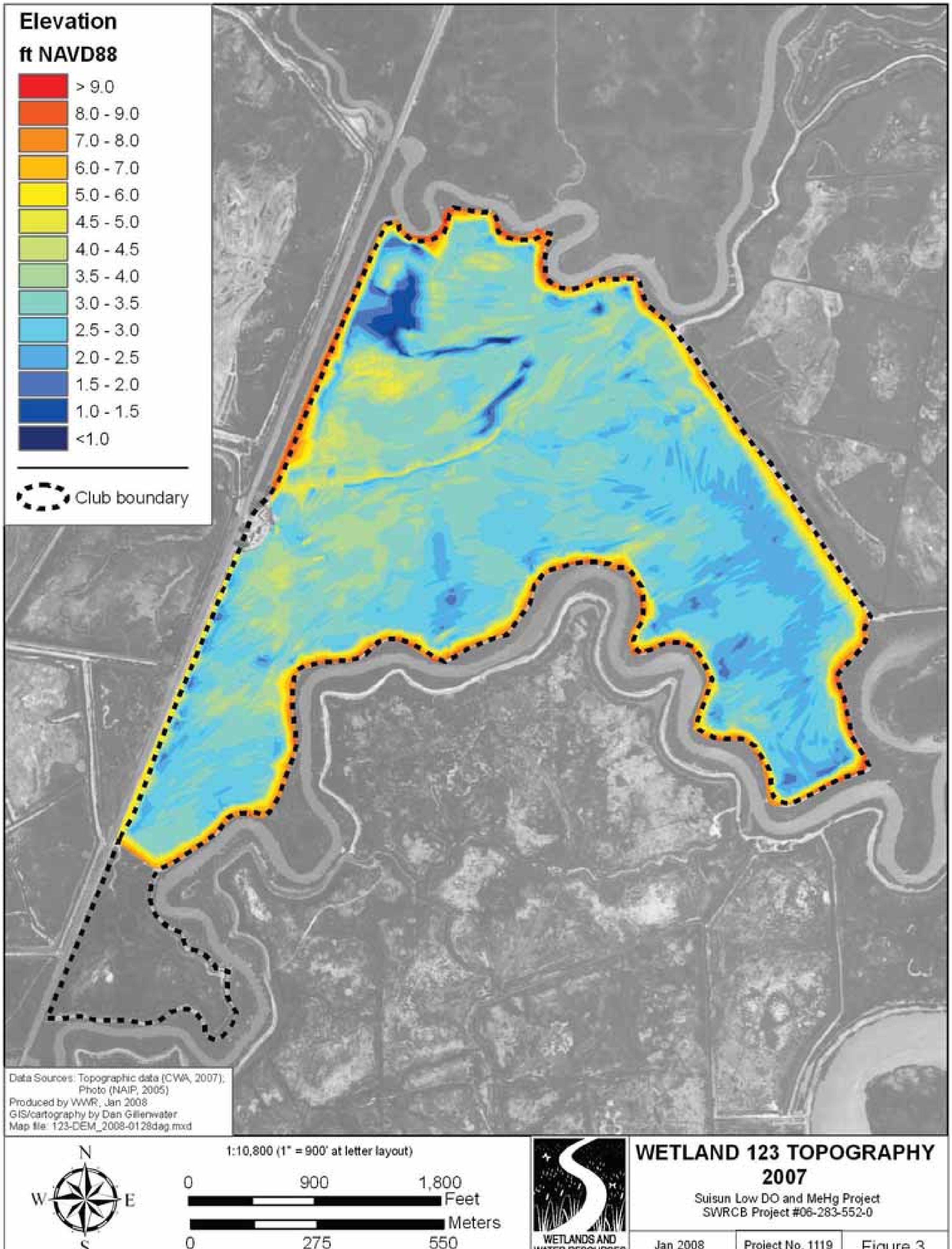




WETLAND 112 TOPOGRAPHY 2007

Suisun Low DO and MeHg Project
SWRCB Project #06-283-552-0

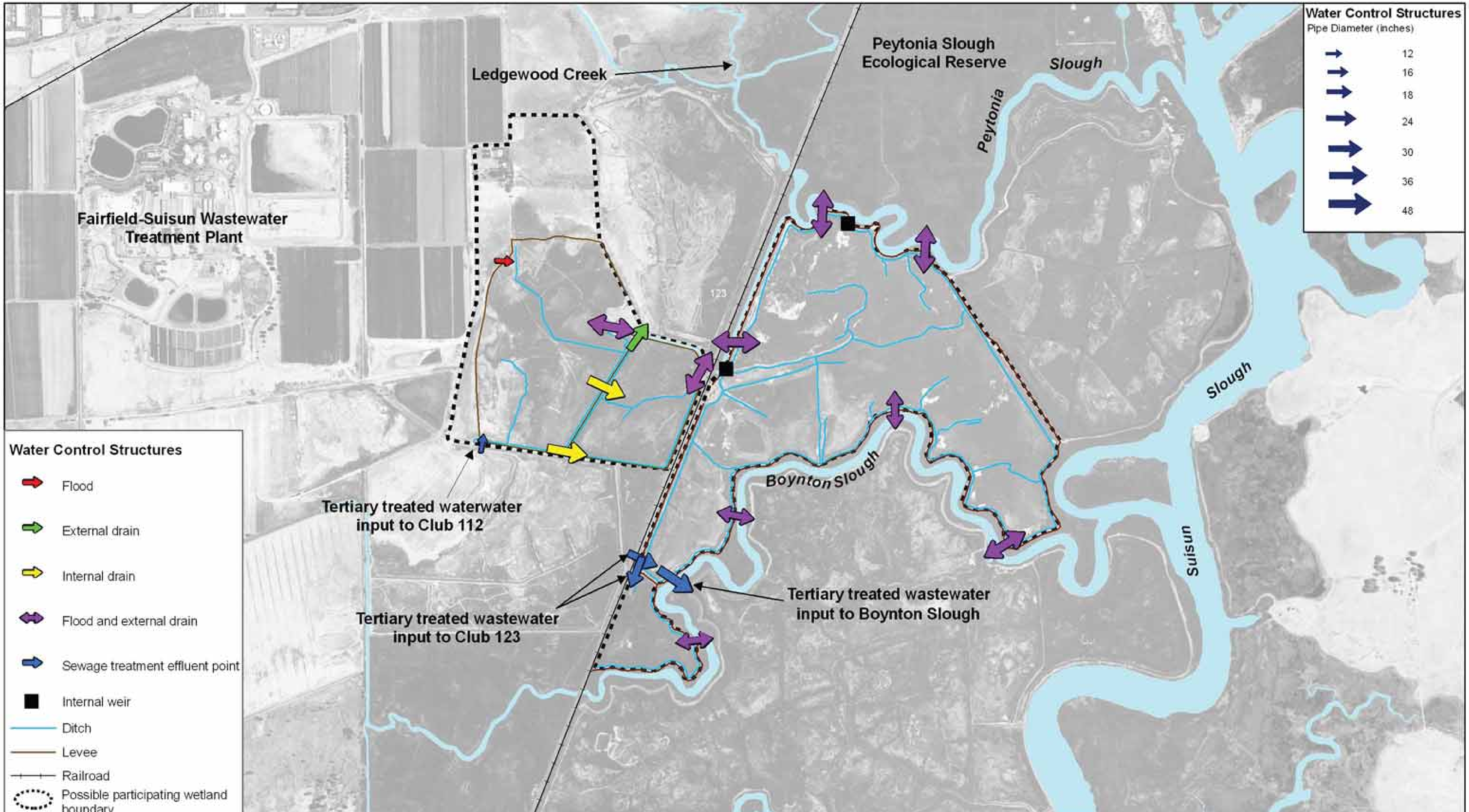
Jan 2008	Project No. 1119	Figure 2



WETLAND 123 TOPOGRAPHY 2007

Suisun Low DO and MeHg Project
SWRCB Project #06-283-552-0

Jan 2008	Project No. 1119	Figure 3

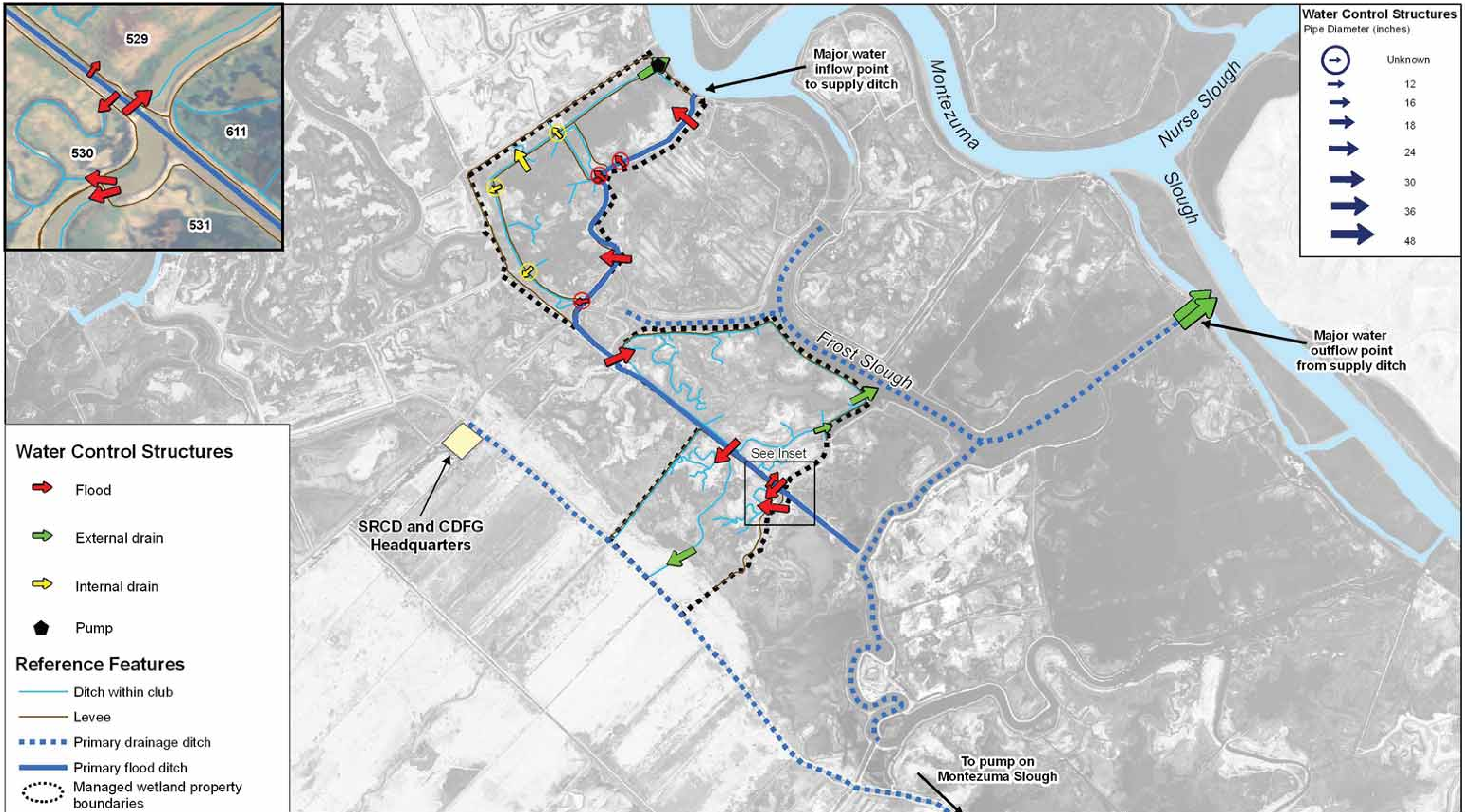


Data sources: SRCD (control structures, levees, channels):
NAIP (photo, 2005)
Produced by WWR, February 2010
Map file: water-flow-routes_North_BL_1119_2010-0217dg.mxd

MAJOR WATER FLOW ROUTES AND HYDROLOGY: CLUBS 112 AND 123

Suisun Low DO and MeHg Project
SWRCB Project #06-283-552-0

February 2010 | Project No. 1119 | Figure 4

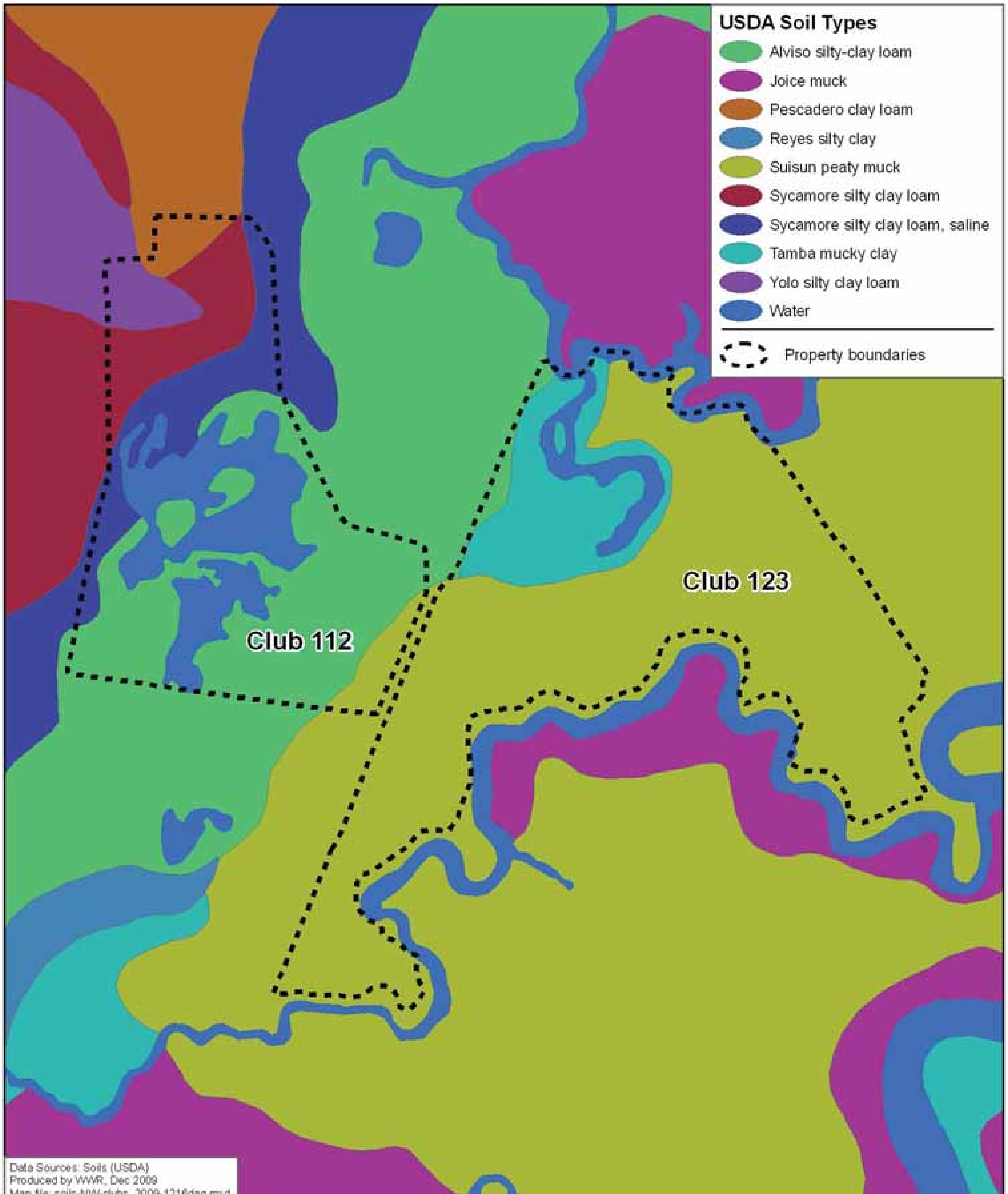


Data sources: SRCD (control structures, ditches, levees); NAIP (photo, 2005)
Produced by WWR, Feb 2010
Map file: water-flow-routes-central_1119_2010-0217dag.mxd

MAJOR WATER FLOW ROUTES AND HYDROLOGY: CENTRAL CLUBS

Suisun Low DO and MeHg Project
SWRCB Project #06-283-552-0

February 2010	Project No. 1119	Figure 5



N
W E
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1:14,400 (1" = 1,200' at letter layout)

0 1,200 2,400 Feet

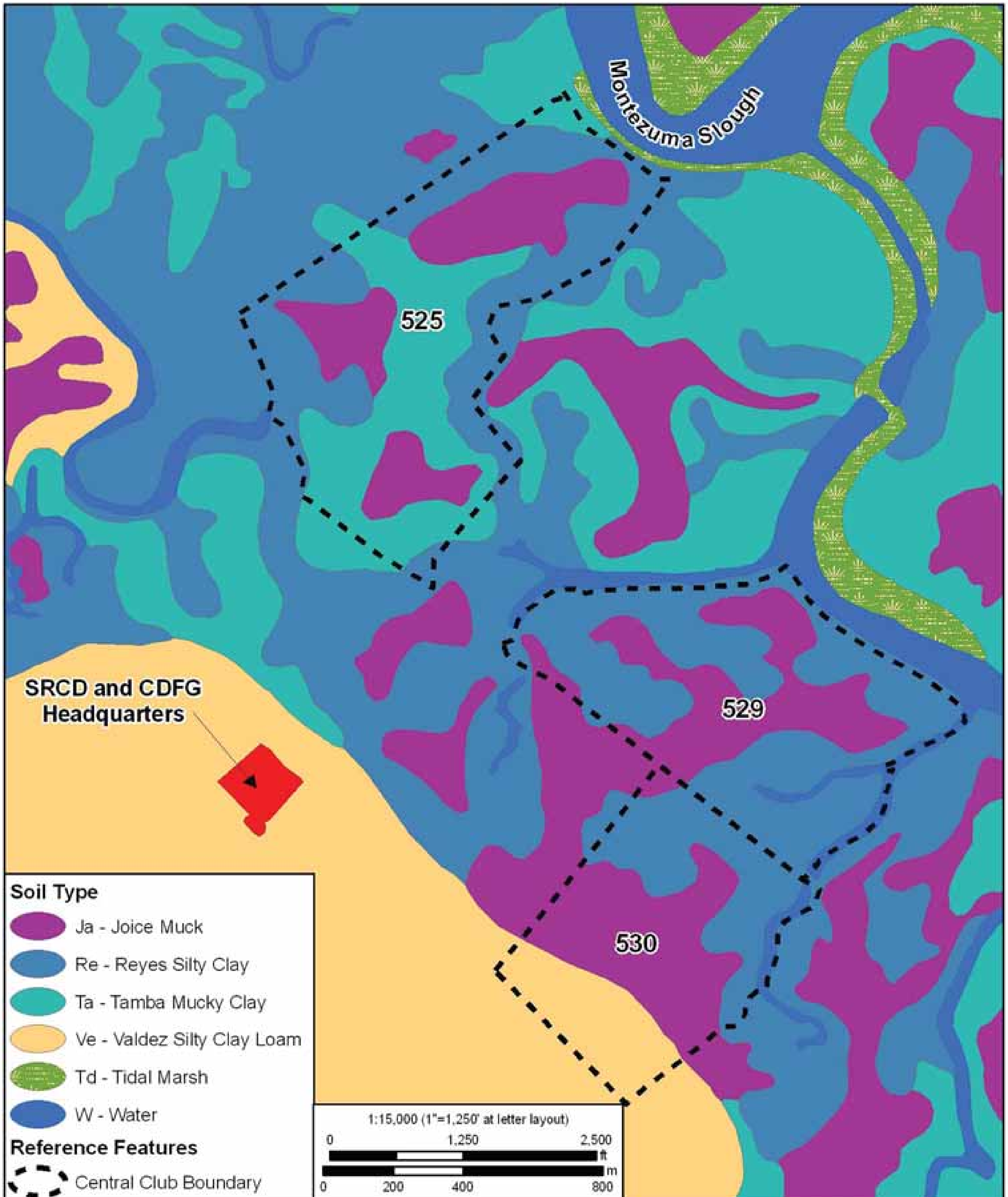
0 350 700 Meters

WETLANDS AND WATER RESOURCES

USDA SOIL TYPES NORTHWEST CLUBS

Suisun Low DO and MeHg Project
SWRCB Project #06-283-552-0

December 2009	Project No. 1119	Figure 6



Data Sources: club boundaries (SRCD), soils (USDA 1977)
Produced by WWR, February 2010
Map File: Central-Clubs-soils_1119_2010-0217lee.mxd

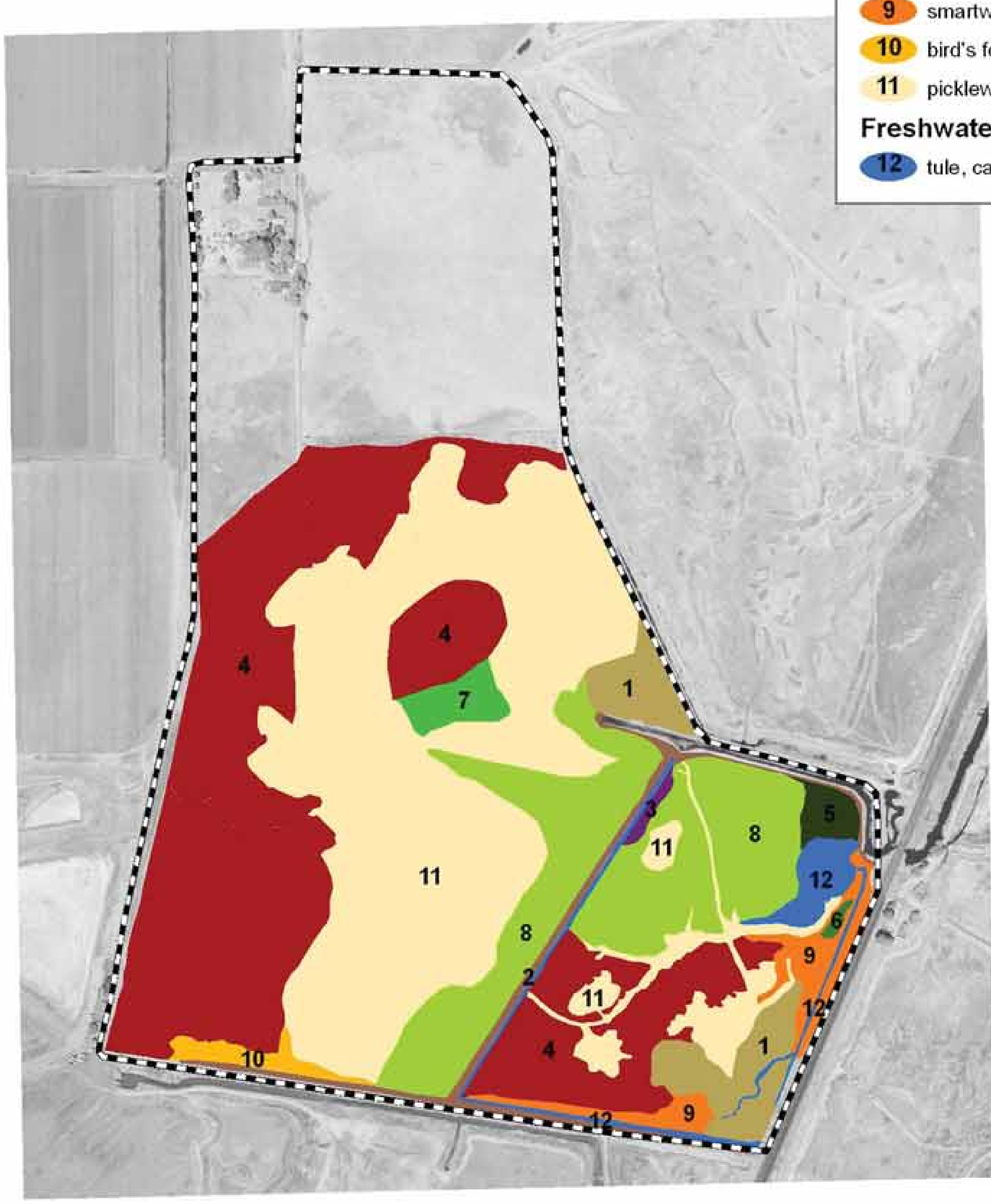
WETLANDS AND WATER RESOURCES

SOIL TYPES
CENTRAL WETLAND CLUSTER
PROPERTIES 525, 529, 530

Suisun Low DO and MeHg Project
SWRCB Project #06-283-552-0

February 2010	Project No. 1152	Figure 7

Note: Vegetation color maps are different in Club 112 and 123.



Vegetation Assemblages

Upland Assemblages

- 1 upland and annual grasses
- 2 upland, ruderal and levee

Saline Wetland Assemblages

- 3 fat hen and saltgrass
- 4 saltgrass and pickleweed

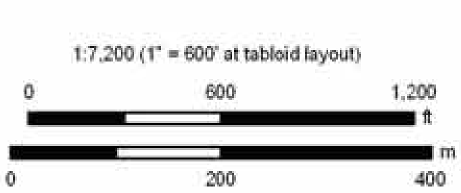
Brackish Wetland Assemblages

- 5 alkali bulrush and fat hen
- 6 baltic rush
- 7 fat hen
- 8 smartweed and pickleweed
- 9 smartweed and fat hen
- 10 bird's foot trefoil and fat hen
- 11 pickleweed and swamp timothy

Freshwater Wetland Assemblages

- 12 tule, cattail and smartweed

Property Boundary



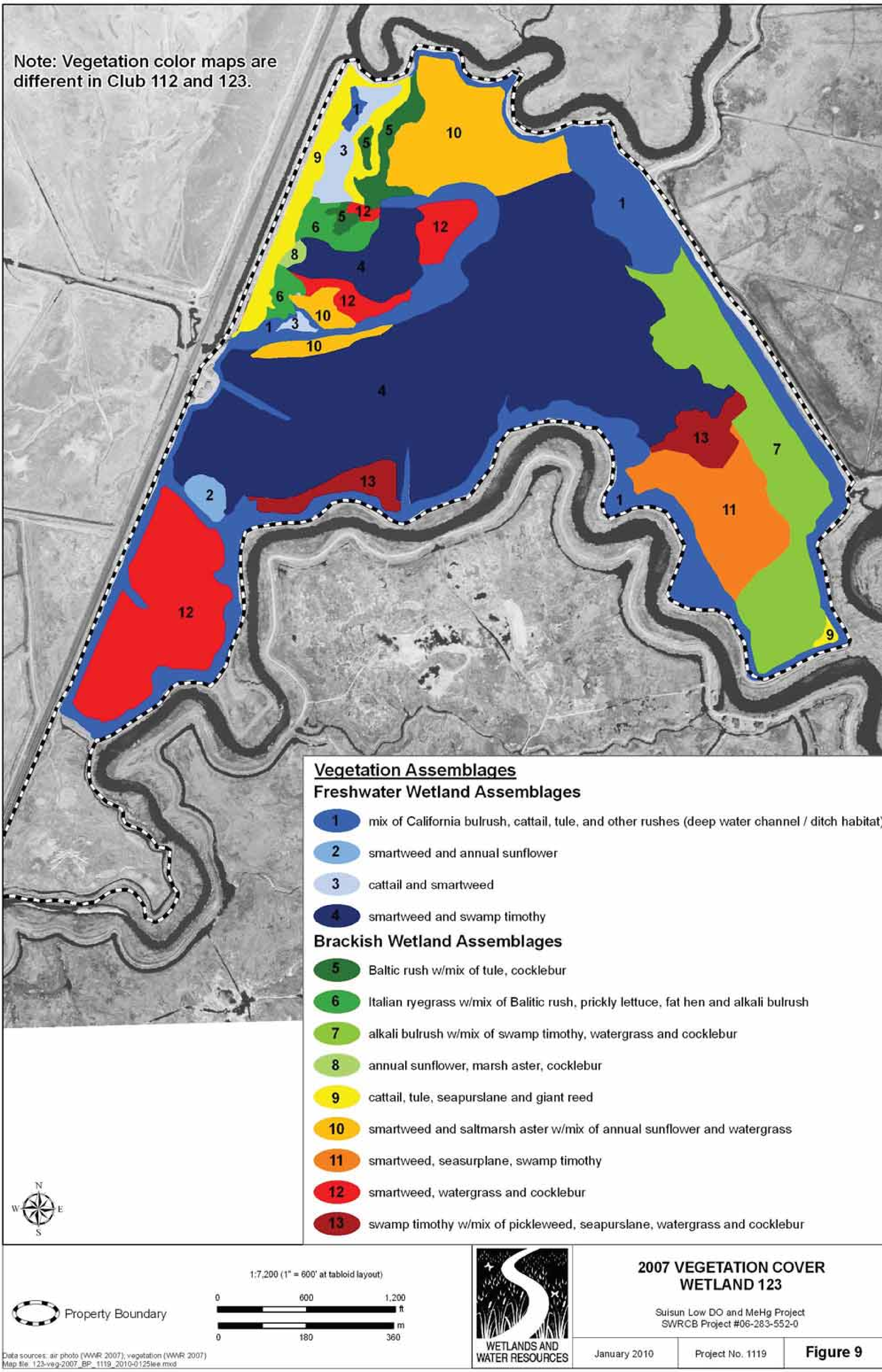
Data sources: air photo (WWR 2007); vegetation (WWR 2007)
Map file: 112-veg-2007_BP_1119_2010-0125lee.mxd

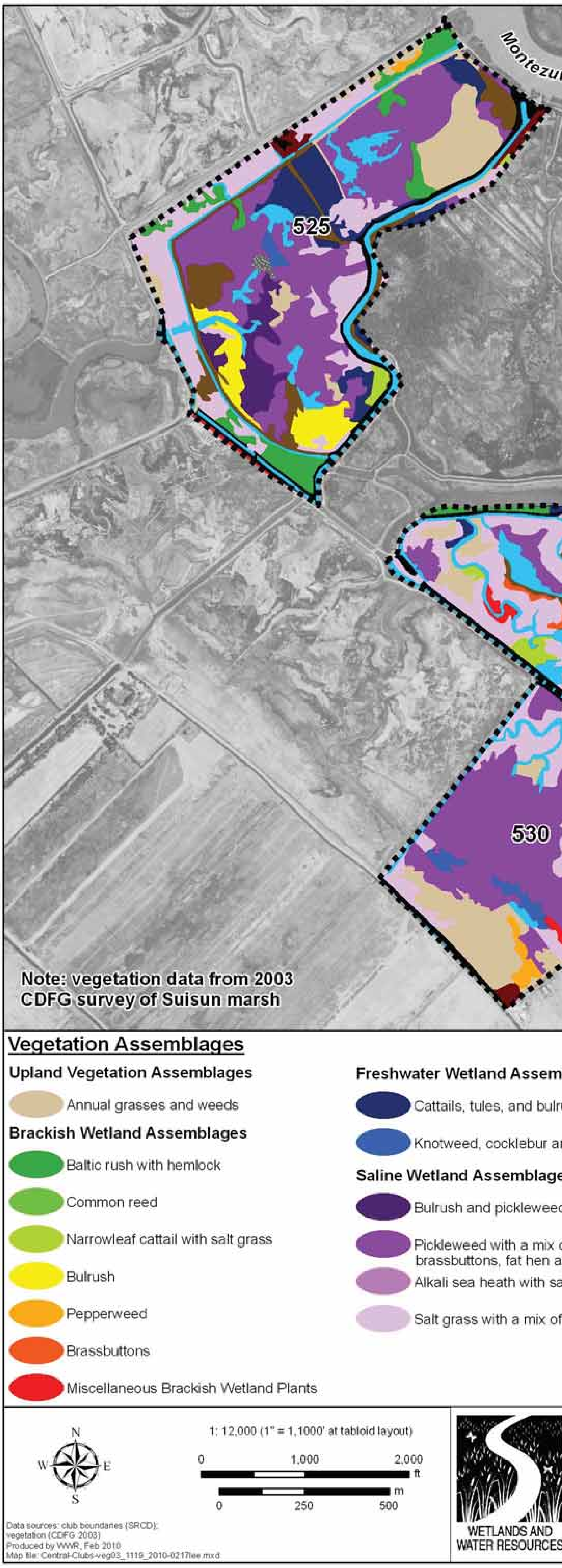
WETLANDS AND WATER RESOURCES

2007 VEGETATION COVER
WETLAND 112

Suisun Low DO and MeHg Project
SWRCB Project #06-283-552-0

January 2010	Project No. 1119	**Figure 8**


Note: Vegetation color maps are different in Club 112 and 123.
Vegetation Assemblages
Freshwater Wetland Assemblages
1 mix of California bulrush, cattail, tule, and other rushes (deep water channel / ditch habitat)
2 smartweed and annual sunflower
3 cattail and smartweed
4 smartweed and swamp timothy
Brackish Wetland Assemblages
5 Baltic rush w/mix of tule, cocklebur
6 Italian ryegrass w/mix of Balitic rush, prickly lettuce, fat hen and alkali bulrush
7 alkali bulrush w/mix of swamp timothy, watergrass and cocklebur
8 annual sunflower, marsh aster, cocklebur
9 cattail, tule, seapurslane and giant reed
10 smartweed and saltmarsh aster w/mix of annual sunflower and watergrass
11 smartweed, seasurplane, swamp timothy
12 smartweed, watergrass and cocklebur
13 swamp timothy w/mix of pickleweed, seapurslane, watergrass and cocklebur
N
W E
S
Property Boundary
1:7,200 (1" = 600' at tabloid layout)
0 600 1,200 ft
0 180 360 m
Data sources: air photo (WWR 2007); vegetation (WWR 2007)
Map file: 123-veg-2007_BP_1119_2010-0125lee.mxd
WETLANDS AND WATER RESOURCES
2007 VEGETATION COVER
WETLAND 123
Suisun Low DO and MeHg Project
SWRCB Project #06-283-552-0
January 2010
Project No. 1119
Figure 9



VEGETATION ASSEMBLAGES
CENTRAL WETLAND CLUSTER
PROPERTIES 525, 529, 530

Suisun Low DO and MeHg Project
SWRCB Project #06-283-552-0

February 2010 | Project No. 1119 | Figure 10

Tables

Table 1: Club Characteristics

Characteristic	Club 112	Club 123	Club 525	Club 529	Club 530
Acreage					
Club total	206	281	188	150	115
Flooded	90	210	137	72	53
Mean marsh elev (ft NAVD88)	4.79	3.03	NA	NA	NA
Volume at shoot level (ac-ft)	78 - 133	223 - 337	NA	NA	NA
Mean Depth at shoot level (ft)	0.71 - 1.21	0.97 - 1.47	NA	NA	NA
Water sources					
Peytonia Slough, mainstem		X			
Peytonia Slough, dead-end branch	X	X			
Boynton Slough		X			
Treatment Plant	X	X			
Montezuma Slough, fish-screened extension			X	X	X
Receiving water bodies					
Peytonia Slough, mainstem		X			
Peytonia Slough, dead-end branch	X	X			
Boynton Slough		X			
Montezuma Slough, mainstem			X		
Frost Lake (non tidal)				X	
Poleline Ditch (non-tidal)					X
Vegetation (%, acres)					
Upland	5%, 10 ac	0%, 0 ac	9%, 17 ac	7%, 10 ac	14%, 16 ac
Saline wetland	51%, 105 ac	0%, 0 ac	48%, 90 ac	52%, 78 ac	67%, 77 ac
Brackish wetland	15%, 31 ac	37%, 104 ac	11%, 21 ac	7%, 10 ac	4%, 5 ac
Freshwater wetland	1%, 3 ac	52%, 146 ac	8%, 15 ac	2%, 4 ac	3%, 4 ac
Barren			14%, 27 ac	5%, 8 ac	4%, 4 ac
No data (open water)			10%, 18 ac	27%, 40 ac	8%, 9 ac
No data (outside area of interest)	28%, 57 ac	11%, 31 ac			
Soils					
Alviso silty clay loam (An)	41%, 84 ac	1%, 4ac			
Sycamore silty clay loam (Sr)	12%, 24 ac				
Sycamore silty clay loam, saline (St)	14%, 28 ac				
Valdez silty clay loam (Vc)					23%, 27 ac
Yolo silty clay loam (Ys)	4%, 9 ac				
Pescadero clay loam (Pc)	3%, 6 ac				
Reyes silty clay (Re)			38%, 72 ac	64%, 96 ac	31%, 36 ac
Tamba mucky clay (Ta)		15%, 41 ac	35%, 65 ac		
Suisun peaty muck (Sp)	3%, 7 ac	79%, 223 ac			
Joice muck (Ja)			27%, 51 ac	32%, 48 ac	43%, 49 ac
Water (W)	23%, 48 ac	5%, 13 ac		4%, 6 ac	3%, 3 ac
Surface water salinity (ppt)**					
Mean	2.60	N = 3.16; S = 3.90	NA	NA	NA
SD	2.43	N = 1.68; S = 1.98	NA	NA	NA

Notes:

*112 shoot level = 5.5-6.0 ft NAVD88; 123 shoot level = 4.0-4.5 ft NAVD88

** N = northern (Peytonia) side of club 123; S = southern (Boynton) side of club 123

Table 2: Club 112 and Club 123 Management Calendar

Club	Year	Month	Dryland Activities: Mow-ing [1]	Dryland Activities: Discing	Dryland Activities: Spraying	Management goal: Salt leaching	Management goal: Vegetation Irrigation	Management goal: Waterfowl use	Management action: Flood	Management action: Pre-flood [2, 3]	Management action: Drain	Management action: Circulate
123	Pre-Study	Oct-06						x				x
123	Pre-Study	Nov-06						x				x
123	Pre-Study	Dec-06						x				x
123	Pre-Study	Jan-07						x				x
123	Pre-Study	Feb-07				x		x	x		x	
123	Pre-Study	Mar-07				x		x	x		x	
123	Year 1	Apr-07			125 ac.			x				
123	Year 1	May-07										
123	Year 1	Jun-07										
123	Year 1	Jul-07										
123	Year 1	Aug-07	5 ac.	60 ac.								
123	Year 1	Sep-07						x	x	x	x	
123	Year 1	Oct-07						x				x
123	Year 1	Nov-07						x				x
123	Year 1	Dec-07						x				x
123	Year 1	Jan-08						x				x
123	Year 1	Feb-08				x		x	x		x	
123	Year 1	Mar-08				x		x	x		x	
123	Year 2	Apr-08			120 ac.			x				
123	Year 2	May-08										
123	Year 2	Jun-08										
123	Year 2	Jul-08										
123	Year 2	Aug-08	5 ac.	60 ac.								
123	Year 2	Sep-08						x	x	x	x	
123	Year 2	Oct-08						x				x
123	Year 2	Nov-08						x				x
123	Year 2	Dec-08						x				x
123	Year 2	Jan-09						x				x
123	Year 2	Feb-09				x		x	x		x	
123	Year 2	Mar-09				x		x	x		x	
112	Pre-Study	Oct-06						x	x		x	x
112	Pre-Study	Nov-06						x				x
112	Pre-Study	Dec-06						x				x
112	Pre-Study	Jan-07						x				x
112	Pre-Study	Feb-07				x		x	x(3)		x(3)	
112	Pre-Study	Mar-07				x		x				
112	Year 1	Apr-07			25 ac.			x			x	
112	Year 1	May-07					x	x	x(2)		x (2)	
112	Year 1	Jun-07					x	x	x(2)		x	
112	Year 1	Jul-07					x	x			x	
112	Year 1	Aug-07										
112	Year 1	Sep-07	80 ac.					x		x		
112	Year 1	Oct-07						x	x		x	x
112	Year 1	Nov-07						x				x
112	Year 1	Dec-07						x				x
112	Year 1	Jan-08						x				x
112	Year 1	Feb-08				x		x	x(3)		x(3)	
112	Year 1	Mar-08				x		x				
112	Year 2	Apr-08			25 ac.			x			x	
112	Year 2	May-08					x	x	x (2)		x (2)	
112	Year 2	Jun-08					x	x	x (2)		x	
112	Year 2	Jul-08					x	x			x	
112	Year 2	Aug-08										
112	Year 2	Sep-08	80 ac.					x				
112	Year 2	Oct-08						x	x	x	x	x
112	Year 2	Nov-08						x				x
112	Year 2	Dec-08						x				x
112	Year 2	Jan-09						x				x
112	Year 2	Feb-09				x		x	x (3)		x(3)	
112	Year 2	Mar-09				x			x		x	

1 Mowing in 2007 was done with rotary deck mower. Mowing in 2008 was done with flail mower

2 Pre-flood is a preliminary wetting of the marsh plain before full fall flood-up to saturate the soils, establish flow paths on the marsh plain, and accelerate the decomposition of dead organic matter.

3 The pre-flood at Club 123 in 2008 was followed by a 6 day drying period

Appendix B: Club Hydrology

The Hydrology of Managed Wetlands Studied in the Suisun Low DO and MeHg Project, Suisun Marsh

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Abstract

This hydrologic study is one component in a compressive assessment of the impacts of managed wetland operations on the greater Suisun Marsh and their role on depressing DO concentrations. For this study, two managed wetlands (Wetlands 112 and 123) were studied. Beginning in late September, these two wetlands are flooded, drained and reflooded again to condition soils, establish flowpaths within the wetlands, and accelerate aerobic decomposition of organic matter prior to the start of the waterfowl hunting season. Water levels are then maintained relatively constant under quasi-steady state conditions until around February around which time wetlands are drained and reflooded two or three times to leach salts from the soils. In late spring, the fields are drained again to allow summer agricultural activities in support of waterfowl habitat enhancement. Tidal inputs and outputs to these wetlands overwhelm climatic effects from evaporation and precipitation. Fairfield-Suisun Sewer District (FSSD) turnouts into the two managed wetlands are managed by the landowners to provide tertiary treated wastewater from FSSD. This treated wastewater is a significant source of water to this wetland during the fall. We estimate that on average about 50% of the water onto Wetland 112 during the fall is tertiary treated wastewater. Flood and drain events are the most significant hydrologic events for these wetlands. During flooding of the wetlands, water levels in the wetlands are raised to about the same elevations from early September through April. Water levels are raised to about 5.75 +/- 0.25 ft-NAVD at Wetland 112 and about 4.0 +/- 0.25 ft-NAVD at Wetland 123. Thus, these flood events throughout the year have similar amounts of surface water exchange. Over a period of a week, average water volume on each wetland during each tide cycle increases from about 20 – 80% but can be over 100%. Drain events typically decrease average water volumes for each tide by 20 to 40%. During single flood event period, several hundreds of acre-feet of surface water floods these wetlands. Wetland 112 has 35 to 113 acre-feet of water flooded onto it during each flood period and Wetland 123 has 170 to 360 acre-feet. These dramatic increases and decreases in water volume are in contrast to the remainder of the fall and winter period during which water volumes change on the order of +/- 2 to 5% during each tide event. During this less volatile period, preferential flow would be expected along wetland ditches though on marsh plains the water is expected to be relatively quiescent and HRTs are expected to be on the order of many days to a few weeks. In addition to the change in surface water volume, the soils go from unsaturated to saturated conditions during the first fall flood event. The soils in Suisun Marsh are very porous and our wetlands had approximately 20 – 25% of pore space available for saturation. The soil data for these wetlands resulted in a prediction that 4 – 8 inches of water is required to saturate their soils which translated into 100 – 125 ac-ft for each wetland. When considered in the context of the surrounding system, the hydrologic management of the wetlands impacts the surrounding sloughs most greatly during the fall. At that time of the year, the sloughs experience reverse flow and depressed DO levels. Reverse flow is likely a combination of minimal riverine runoff in this Mediterranean climate as well as the water demand from the managed wetlands in Suisun MarshDuring the remainder of the flooded period (i.e. winter, spring), wetland hydrologic management impacts on the surrounding sloughs seems less because of more constant flow in the downstream direction and greater flow magnitudes.

Introduction

Severely low dissolved oxygen (DO) events resulting from environmental conditions and management actions in some managed wetlands adversely impact the aquatic ecosystem of various sloughs in Suisun Marsh (Schroeter and Moyle 2004). Peytonia, Boynton, and Suisun Sloughs in the northwest Marsh have exhibited the most significant low DO problems (Schroeter and Moyle 2004). Most of the adjacent managed wetlands are dry during the summer and early fall months when land managers carry out maintenance activities with the prime goal of enhancing waterfowl habitat. These systems are then flooded in the fall with water maintained on the marshes into mid-spring. Low DO waters have been documented at the fall flood-up cycle that upon release send low DO plumes into receiving waters (tidal sloughs) impacting aquatic organisms, including killing at-risk fish species and impairing valuable fish nursery habitat (Schroeter and Moyle, 2004). Wetland releases are also expected to have elevated organic matter (Stringfellow et al, 2007; Engelage et al 2009) with associated biological oxygen demand (BOD), further depressing DO in receiving waters.

Other water quality problems may result from depressing DO concentrations. Methyl mercury (meHg) is produced in low DO organic soils in association with bacterial sulfate reduction (Compeau and Bartha, 1985; Berman and Bartha 1986; Gilmour et al, 1992, Benoit et al 2001). Wetlands are areas of high meHg production, cycling and export (St. Louis et al, 1994; Hurley et al, 1995; Rudd, 1995) and Heim et al (2007) found meHg concentrations higher in the marsh interiors than their exteriors, and higher in marshes than in open water. The exact amount of meHg and total mercury tMe exports have not been determined for Suisun managed wetlands. High nutrient loading from these wetlands could exacerbate these problems though the data is not certain at this time (Vaithiyanathan et al, 1996; Gilmour et al 1998)

Past research and outreach efforts into the low DO issue have resulted in the development of a variety of management programs for Suisun Marsh (SRCD, 2010) and within these programs are recommended practices:

- Landowners with mosquito production or low DO problems are currently recommended to conduct an early flood-drain cycle prior to bringing ponds to fall management level.
- Once at fall management level, landowners are recommended to circulate water at highest rate possible until temperatures cool (mid-November).
- Landowners are recommended to avoid wetland discharges to dead end drainage sloughs and to redirect discharges to larger sloughs, in order to maximize mixing with tidal waters and thus minimize low DO sags.
- Implementing water management activities to discourage broadleaf plant growth and encourage physical manipulation of this vegetation prior to fall flooding.

This study's purpose is to develop an understanding of the hydrology and water quality within the wetlands and in the surrounding sloughs in order to develop strategies to minimize water quality and hydrologic impacts to the sloughs and their concomitant ecological effects.

This manuscript describes and quantifies the hydrology of two managed wetlands in the Suisun Marsh by tidal event, estimating volumetric hydrologic exchanges, quantifying precipitation and evaporation, and estimating soil water demand. We use those data to develop water budgets and estimate flows onto and off of the wetlands on a tidal basis, during flood and drain events and seasonally and discuss those events in the context of the hydrology of the surrounding slough system. These results will be used to develop management recommendations for the wetlands to minimize environmental impacts to the surrounding slough system.

Site Description

Suisun Marsh lies north of Suisun Bay of the San Francisco Bay Delta system (Figure 1). Two managed wetlands were studied, Suisun Farms (Wetland 112; Figure 2) and Walnut Creek Gun Club (Club 123; Figure 3). These wetlands are connected to adjacent marsh sloughs via a series of water control structures that allow managers to regulate water levels within the wetlands and exchange with adjacent sloughs.

Methods

A wide variety of hydrologic and physical data were collected at these wetlands: surface water, soil water, climatic and topographic data. These data were processed to develop surface and subsurface water budgets for the sites. Wetland management data were collected based upon SRCD records to aid in interpreting the data. These methods are further discussed below.

Hydrologic and Physical Data

Digital Elevation Models

Topographic surveys of Wetlands 112 and 123 were performed in the summer of 2007 by the California Waterfowl Association (CWA). The topographic data were collected using a Real-Time Kinematic (RTK) differential GPS system, and referenced to various established benchmarks in the project vicinity. DEMs with a 3-ft horizontal resolution and elevations in feet, referenced to the North American Vertical Datum of 1988 (NAVD), were constructed from these data using the 3-D Analyst tools in ArcView v3.2. These DEMs were used to develop stage-volume relationships for each of the managed wetlands for use in later analyses.

Hydrologic Data

Hydrologic monitoring locations are shown in Figure 2 for Wetland 112 and in Figure 3 for Wetland 123. Table 1 describes each station at which hydrologic monitoring was conducted and presents station infrastructure, the time period the station was in service, its placement within the wetland, vegetation characteristics and management conducted. These stations were monitored from August to April 2007 in Year-1 and from September to November 2008 in Year-2. Stilling wells were established at all hydrologic monitoring stations and equipped with staff gauges and reference benchmarks. At perimeter stations, water levels were recorded with multi-parameter datasondes. Water levels were recorded at selected internal monitoring locations using externally vented pressure transducers as stand alone probes or as components of a multi-parameter datasonde. Local elevation reference benchmarks at each monitoring station were surveyed into ft-NAVD and used to convert surface water elevations to ft-NAVD. All stations were set to record data on 15 minute intervals and stations were visited monthly during deployment to calibrate and maintain.

Hydrologic data from others included treatment plant data from Fairfield-Suisun Sewer District (FSSD) who measured treatment plant flow to Suisun Marsh and water volumes to each wetland; and Department of Water Resources continuous water level data for Boynton and Peytonia Sloughs.

Soil Data

NRCS Soil Survey data were compiled for the project using the Web Soil Survey (NRCS 2010). Custom Soil Resources Reports were developed with data describing organic matter content; sand, clay and silt content; saturated hydraulic conductivity; water content at 15 bar (witling point) and 1/3 bar (field capacity); bulk density; and depth to water table (from September thru November). All soil components were described for a soil depth of 0 – 36 inches. These data were presented by soils type for each wetland and the area coverage was estimated for each soil type. Relating soil data to the area coverage of the soil for each wetland, a weighted average for each constituent was calculated for each wetland.

Climate Data

Meteorology data were collected using the Suisun California Irrigation Management Information System (CIMIS) station (Suisun Valley #123): precipitation, temperature, reference evapotranspiration. Crop evapotranspiration (ET) was estimated using crop coefficients:

$$ET = K_c \, ETo$$

where ET is in in day^{-1}, the K_c value is dimensionless, and ETo is the reference crop evapotranspiration in in day^{-1}. K_c values were estimated from Bachand et al (XXX) for rice.

Data Processing and Calculations

Data were processed stepwise to develop water budgets and to allow for statistical analyses of the data and those results:

- Developing tidal water volume exchanges;
- Calculating surface water budgets; and
- Estimating subsurface water budgets.

Developing Tidal Surface Water Volume Exchange

Tidal water volume exchanges onto each club were developed for each island based upon the results of the monitoring locations. Wetland 123 had distinctly different water level trends between the interior stations, the northern perimeter stations and the southern perimeter stations. However, within each region of the wetland, water elevation trended closely. Thus, for each region of Wetland 123, the more reliable stations were identified for Year 1 and Year 2 and the average water trend data from those stations were used to describe the water elevation trends for that region. For Wetland 112, interior and exterior stations trended similarly so all stations were put into a single region and the more reliable stations used to develop a single water elevation trend for Wetland 112 (Table 2). Some data loss occurred at different stations due to battery failure and faulty calibrations.

For each wetland, tidal cycles were identified in the water level time series. Hydrologic trends were flagged with tidal cycle numbers such that the hydrology for each tidal cycle could be quantified: changes in water elevation, high tide elevation, low tide elevation, water volume on, water volume off, net volume exchange. Tidal cycle numbers were also applied to the climate data such that those data could be linked to the hydrologic data and be used in developing surface water budgets.

Water volume exchange for each tidal cycle was developed from the water elevation data using the stage-volume relationships determined from the DEM. These relationships were fitted with curves developed using StatSoft (2008; R^2>99.9%). From those results, the water loss from the island from the first high tide to the low tide and the water gained from the low tide to the final high tide were calculated. Additionally the percent water loss during a high tide ($\%Decrease = Q_{OFF}/Vol_{High}$) and the percent water increase ($\%Increase = Q_{ON}/Vol_{Low}$) were calculated. Water volume onto the wetland was represented as a positive water volume and water volume off was shown as negative water volume.

Surface water budgets

Surface water budgets were developed utilizing data from the tidal cycles identified for each wetland. Relating the initial high water elevation at the beginning of each tidal cycle, the following low water elevation, and the high water elevation at the end of the tidal cycle to the stage-volume relationship (**Error! Reference source not found.**), water volumes discharged, water volumes applied, and net water volumes applied (water volumes applied – water volumes discharged) were determined. These results were combined with evapotranspiration and precipitation data to provide the data needed for a surface water budget:

$$Q_{ON} + P - ET = \Delta Vol_{Increase}.$$

The water budget was divided into two halves to represent the ebb and flood cycle with the budget at each cycle described as

$$Q_{ON} + P/2 - ET/2 = \Delta Vol_{Increase,1/2}.$$

Subsurface Soil Water Storage

Subsurface soil water storage was considered negligible in these systems after their initial flooding as these systems constantly receive tidal water and thus are expected to have negligible subsurface exchange. However, prior to the initial wetland flooding, these systems are maintained drained with a series of ditches and thus at the initial flooding period, soils above the water table go from a non-saturated to saturated condition.

Subsurface storage was calculated using the above-listed NRCS soil survey data. Pore space was calculated from the estimated specific gravity (SG) and bulk density (BD) for the organic and inorganic fractions. A SG = 2.65 was used for the inorganic fraction (Brady and Weil 2002) and a SG = 1.4 was estimated for the organic fraction using data on peat soils and histosols (Bogacz and Roszkowicz 2009; Sing et al 2008; Kalantari and Huat 2008; ISRIC 2010). Using the weighted average of bulk density, percent organic fraction and percent inorganic fraction, a weighted composite pore space was determined for each wetland.

For the first fall flood of each year, we assumed the soils in the profile were between the wilting point and field capacity. Water content was taken from an average of the wetland composited field capacity (1/3 bar) and wetland composited wilting point (15 bar). The percent available pore space for saturation was calculated as the difference between the calculated wetland pore space and the calculated water content.

The amount of water (in inches) needed to saturate the soils was calculated by multiplying the percent available pore space by the depth to the water table. This volume of water was assumed only to be needed during the initial flooding period. A range of time needed to flood the fields was estimated using the range of saturated hydraulic conductivities provided for the soils at each wetland. These conductivities varied over an order of magnitude. Given their range and the uncertainty in the calculations using NRCS data, the saturated hydraulic conductivity was considered a reasonable proxy for hydraulic conductivity in unsaturated conditions.

Wetland Management

The management activities and their timing were provided to us by the SRCD who work closely with the landowners in Suisun Marsh and provide guidance with regard to hydrologic and vegetation management based upon their knowledge and other documents (Rollins, 1981)..

Data Management and Statistical Analyses

A variety of statistical methods including basic descriptive statistics (e.g. means, medians, quartiles, standard deviations), ANOVA (e.g. one-way, two-way, factorial), principle components analyses, and graphical representations (e.g. scatterplots, box plots) were used to investigate trends and assess statistical differences between treatment, with depth and over time (StatSoft 2008). Data was managed with an ACCESS database to allow quick outputs of data under multiple formats and with multiple relationships. The results shown in this study are the key findings from these investigations.

Results

Wetland Management

Mechanical and water management techniques are used by landowners in Suisun March to manage vegetation to achieve a beneficial food source for wetland dependant wildlife, manage for nuisance invasive vegetation, and reduce potential impacts to water quality. Both types of activities were used at Wetlands 112 and 123 during this study and are summarized in

Table 3.

During February 2007 in the first year of the study and following the close of waterfowl hunting season, the water managers at Wetland 112 drained the marsh plain of the wetland and then performed a series of three flood-drain cycles to leach salts from the soils. After the last leach, the water level was held at half of the normal (winter level) height until April 15, when the entire wetland was drained. The water managers then performed two flood-drain irrigations per month in May and June after which point the wetland was drained for the remainder of the summer.

During the first summer (2007) at Wetland 112, 80 acres were mowed using a standard rotary deck mower to reduce the amount of vegetative material available for decomposition and 25-acres of invasive cocklebur *Xanthium spp.* and pepperweed *Lepidium latifolium* were sprayed with herbicides to reduce the numbers of these species. On September 28 water was brought to slightly below shoot level, then immediately drained and reflooded to a desired height for waterfowl season. Once flooded to desired height the water was circulated at the highest rate possible.

The only dryland activity that differed at Wetland 112 in Year-2 was that mowing was done differently, employing a flail mower instead of a rotary deck mower. Water management activities differed slightly also. The initial flooding was extended and water levels in the marsh were kept low for an extended period of time following the first drainage. Table 4 shows the dates of the different draining and flooding water management activities based upon hydrologic data from this study.

At Wetland 123 during February 2007 in the first year of the study and following the close of duck hunting season, the water managers drained the marsh plain of the wetland and then performed a series of three flood-drain cycles to leach salts from the soils. After the last leach, the water level held at half of the normal (Winter level) height until April 15, when the entire wetland was drained for the remainder of the summer.

During August 2007, five acres were mowed using a standard rotary deck mower to reduce the amount of vegetative material available for decomposition, 60 acres of the wetland were disked to reduce the presence of broad-leafed vegetation, and 125-acres of invasive cocklebur and pepperweed were sprayed with pesticides to reduce the numbers of these species. On September 15, 2007, water was brought to fall level or slightly below then immediately drained and reflooded to a desired height for waterfowl season. Once flooded to desired height the water was circulated at the highest rate possible.

Water was managed similarly during the second winter. In the summer, slight changes occurred with a flail-mower was used as opposed to a rotary deck mower and a slight reduction by 5 acres of land treated with herbicides to control invasive cocklebur and pepperweed. Water management in the second summer was also slightly changed. The pre-flood period in September 2008 was followed by a 6-day drying period prior to full flood-up and focused grading in part of Wetland 123 was done to improve circulation and facilitate wetland drainage.

Wetland Topography

Figure 4 shows the DEM for Wetland 112 and Figure 5 shows the DEM for Wetland 123. Overlaid on each map are stage-elevation relationships and the fitted functions. At Wetland 112, for elevations below about 4.5 ft-NAVD the change in water volume is very slight. Above that elevation, increases in elevation correspond to linear increases in stored water volume. A similar result is found for Wetland 123. However, for the wetland the transition elevation is about 2.9 ft NAVD.

For both wetlands, the change in water volume below the transition elevation represents the filling of sloughs and channels within the wetland. As shown on the DEM, only a small percent of Wetland 112 is below 4.5 ft-NAVD and below 2.5 ft-NAVD for Wetland 123. Below those elevations, water is primarily stored in sloughs or small ponded zones. Above those elevations, the wetlands show broad areas with generally increasing elevations towards the perimeter levees.

Station and Regional Hydrologic Trends within Wetlands

Figure 6 and Figure 7 show temporal trends in water elevation at the instrumented perimeter and internal stations for Wetlands 112 and 123 respectively.

Wetland 112 stations are categorized by two wetland regions: stations internal to the wetland and station on its perimeter (Figure 2). Perimeters stations show the low water level is approximately 2.75 ft-NAVD when the wetland is drained, and during the winter period is flooded to about 6 ft. These two stations were located in the perimeter ditch near the water control structures on the inland side of the wetland levee (Table 1).

The two internal stations are located in the marsh plain (Table 1). Both internal stations showed similar temporal trends and maximum water levels. Two differences are found between the data from these two stations. First, the minimum water level differs and is controlled by marsh plain elevation, 5 ft-NAVD at Station 112-4 and 4 ft-NAVD at Station 112-5. Second, the temporal trends differ slightly and is likely due factors within the marsh. Station 112-4 differs from 112-5 in that 112-5 receives water from a marsh channel pulling water from the north whereas 112-4 pulls water from the south. Thus, 112-5 would be expected to have more hydrologic connectivity with the northern perimeter station 112-1 then would 112-4. The temporal data supports that contention.

Wetland 123 stations are categorized by three regions: northern perimeter stations along or influenced by Peytonia Slough; southern perimeter stations along Boynton Slough; and internal stations. The perimeter stations are located in open water in the perimeter ditch and situated near water control structures (Table 1). Figure 7 shows the water level trends for each region. The northern and southern perimeter stations have a minimum water elevation at about 1.5 ft NAVD and a maximum at about 4.5 ft NAVD. The temporal trends for stations within a region track each other closely showing the high connectivity with and control by Boynton Slough in the south and Peytonia Slough in the north.

The internal stations are located within the marsh plain and have diverse vegetation communities (Table 1). These stations have elevations ranging from 2 – 3.5 ft NAVD. Station 17 is near a discharge turnout for the wastewater treatment plant. The temporal trends from these internal stations track each other very closely and more closely then at the stations in Wetland 112. The only major difference between stations is the differences in minimum water elevations recorded at these stations. Those elevations are controlled by the marsh plain elevation at each station. The stations are generally located by marsh channels, half are in the marsh plain, and one receives water from the WWTP. None of these factors seem to greatly affect water elevation trends. Minimum water elevations are in the range of 2.3 and 3.3 ft-NAVD and maximum are at about 4.5 ft-NAVD.

Figure 8 compares the perimeter and internal hydrologic trends at each wetland. At Wetland 112, longterm trends are similar with internal trends generally lagging behind perimeter trends as would be expected. During the flooded period from October thru February, cyclic water level trends generally about one half foot occur on approximate fourteen day periods. Wetland 123 has similar trends: the interior site elevations at Wetland 123 lag behind the exterior site elevation changes and a fourteen day cycle occurs. However, at Wetland 123, the perimeter and interior water elevation trends are more similar then at Wetland 112.

Figure 9 and Figure 10 temporally focus the data on the changes in interior and perimeter water elevations during fall and spring draining and flooding events. During Fall of Year 1, Wetland 112 experienced a flood-drain-flood event consisting of an initial flood (4.5 days), a drain event (4.5 days) and a final flood (5.4 days; Table 4). During the winter, Wetland 112 experienced three drain-flood events from the end of January through late February. Draining took 3 – 5 days and flooding took 4 – 6 days. Finally, the system was drained in the spring after the instrumentation ceased data collection.

In the second fall, Wetland 112 experienced a flood-drain-flood. The first flood event began on October 1 and was parsed out in two parts. When the wetland was drained beginning on October 19, it was kept drained for about 5 days before it was again reflooded from October 27 through November 1 (Table 4, Figure 6). This flood-drain-flood event differed from that of the previous year in several ways. First, the event was extended over a much longer period. During the first year, the flood-drain-flood event occurred over nine days whereas in the second year it occurred over about 35 days. Second, in the first year the wetland was slowly flooded up during the initial flooding over about twenty days compared to a shorter more rapid flooding of 4.5 days during the first year. Finally, in the second year the internal stations were drained down for about five days and this prolonged drained period did not occur during the first year.

At Wetland 123, water can enter the wetland from both Peytonia and Boynton sloughs (Figure 3), both of which have nearly identical tidal signatures based upon data from this study (not shown). During the first year fall period, the system was flooded beginning on September 18 for about 4.5 days, drained beginning September 23 for about 4.5 days and then reflooded beginning September 27 for about 5.5 days (Figure 7, Table 4). During the first fall, the northern side experience greater tidal amplitude then the southern sites during flood events whereas the southern sites experienced greater amplitude then the northern sites during drain events. These trends suggested that during the first fall, efforts were made to flood from the north and drain to the south. This trend was absent during the February drain flood events. These events occurred from February 9 through March 16 and consisted of drain events of about 4 days and flood events of 11 and 5 days.

The second fall at Wetland 123 was managed similarly to the first fall though flooding began about 4 days later and took longer with flooding taking a longer time. One difference during the second fall was after the drain period a drying period which resulted in low water levels for about 4 or 5 days occurred as discussed earlier with regard to wetland water management. During this second fall, the data does not suggest water was preferentially flooded from the north and flowed to the south.

Climate

Figure 11 presents evaporation data for Wetlands 112. Evaporation trends similarly at both sites and ranged from around 0.05 in/day in the winter to about 0.25 in/day in the summer. Figure 12 present precipitation data During the first year of the project, there were four rain events that exceeded one inch total and another six or so rain events over 0.5 inches each. In the second year of data collection, two small rain events occurred.

Surface Water Volume Exchange

Figure 13 shows net water volumes on and off Wetlands 112 and 123 by date at which each tide event began. Water flows onto the wetlands in proportion to the tidal events. More water flows on during high-high tide events than during high tide events. The water volume exchanges are cyclical, on an approximate 14 day cycle, and greater at Wetland 123 as compared to Wetland 112. Discharge events are much more rapid and sudden then flooding events. Figure 9 and Figure 10 first show this result in that time to flood is always greater then time to drain. But Figure 13 shows this more clearly with water being dramatically discharged over one or two days during drain cycles (as indicated by sharp downward peaks). Finally, the initial flooding and draining in late September and early October cause the greatest surface water exchanges during the fall though surface water volumes exchanges in the winter period are of similar magnitude. For instance, at Wetland 112, the fall flood brings on and off the fields up to 2 – 3 inches per tidal event but in early January four inches come onto the fields during tidal events and during January and February three drain events near or over two inches occur. At Wetland 124 similar trends are shown with large fall flood and drain events but also very large flood and drain events occurring during the winter as well.

As discussed in the Methods, we estimated surface flows on and off the fields using water budgets. Figure 14 show these surface flow results on a weekly basis. In this figure, flow on, flow off and the net irrigation is shown. Flow onto the wetlands is represented as positive flow and flow off the wetlands is represented as negative flow. Flow is standardized against the area of each wetland and is shown in inches per week. Figure 15 shows these flows as a percent increase or decrease in water volume on the wetlands. Table 5 and Table 6 summarize the values for Wetlands 112 and 123 in water budgets.

These figures provide some additional information. For Wetland 112, the amount of water applied typically ranges from about 1.5 – 6.7 inches (10 – 90%) and averages about 4 inches (Table 5). Weekly discharges range from about 1 to 6.5 inches, averaging around -3.6 inches.

Wetland 123 has greater volumes of water applied and discharged. Weekly applications range from about 1 - 13 inches (10 – 90%), averaging about 8 inches. Weekly discharges range 0 to 14 inches, averaging about 7 inches. For both wetlands, flooding and drainage events tend to show up as weeks with greater applied or discharged water (Table 5). During those weeks of flooding at Wetland 112, typically 5 – 8 inches of water is applied whereas during weeks of drainage 5 – 9 inches of water is discharged. For Wetland 123, 6 – 16 inches of water is applied during weeks of flooding and 6 – 22 inches of water is discharged during weeks of draining. These events tend to have an effect on the net water applied. At Wetland 112, 75% of net water applications outside the 10 – 90% percentile (extreme events) occur during either a drain or flood event, corresponding to a weekly discharge greater than 34 ac-ft or a weekly application greater than 58 ac-ft. At Wetland 123, 85% the extreme events are associated with flood or discharge periods. These events correspond to weekly discharges greater than 120 ac-ft or weekly applications greater than 132 ac-ft.

Table 4 presents the drain and flood events that occurred during these periods individually with calculations of changes in water elevations, wetland water volume and flows. Drain and flood events average around 260 ac-ft at Wetland 123 with average net drain flows from the wetland averaging around 30 cfs and average net flood flows of 20 cfs. For Wetland 112 drain events average around 75 ac-ft and flood events around 60 ac-ft. Net drain flows from Wetland 112 average around 14 cfs during the drain events. During flooding, net flood flow averages around 7 cfs.

Finally, an important consideration in considering discharge is the percent change in current conditions during any single flooding or drainage event (**Error! Reference source not found.**). Figure 15 shows the percent change over existing average water levels on a weekly average. The value shown in this figure represents the weekly average discharge (or application) divided by the average initial water volume. From this calculation, the most dramatic changes in the system occur during the initial flooding period in the fall during which applied water increases water volumes in the range of 30 – 100% and during discharge periods in which water discharges average 30 – 70% of initial water volumes. These changes are dramatic not because the total water application or drainage rates. Figure 14 shows that these rates though high are not extreme in comparison to other times of the year. Rather, the initial hydrologic conditions are the primary reasons. For instance, the weeks of 9/30/07 and 11/25/07 at Wetland 112 have very similar water application and discharge values (Figure 14). However, because the system was relatively drained initially during the week of 9/30/07, the percentage affect is 3 – 4 times higher than during the week of 11/25/07.

Table 5 and Table 6 present the seasonal water budgets for the wetlands during the two main water periods: late summer through fall and winter through early spring. When fall begins, the fields are drained. By the end of fall, there is standing water. During the fall, about 58 inches of water was applied and about 50 inches of water was discharged from Wetland 112. At Wetland 123, 140 inches were applied and 125 inches were discharged during the first fall (about 150% more than at Wetland 112). The difference represents the amount of water stored on the fields. Thus by these calculations, at Wetland 112 approximately 8 inches of water was stored whereas in Wetland 123 approximately 15 inches were stored. During this period ET demands are about 2.5 inches greater then precipitation.

For the winter period, Wetland 112 has about 70 inches applied and discharged. At Wetland 123, 98 inches of water is applied but 103 inches are discharged. ET demands during this period were about 10% greater than precipitation.

Soil Saturation Demand

During the initial fall flood, a portion of the water applied goes to water storage in the soil. Based upon our analyses of the NRCS (2010) soils data for the two wetlands, we estimate several inches of applied water initially are needed to saturate the soils above the water table. We estimate 8 inches and 126 ac-ft are needed at Wetland 112 and 4 inches and 110 ac-ft are needed at Wetland 123 (Table 8). Those estimates have a lot of uncertainty so we estimate 4 -11 inches required at Wetland 112 and 2 – 6 inches at Wetland 123 based upon a +/- uncertainty.

Sewer District Contributions

The FSSD discharges about 1300 ac-ft (960 – 2100) of tertiary treated wastewater per month with an average flow of 42 – 44 ac-ft/d (21 – 22.5 cfs). Most the discharge is to Boynton Slough though a number of turnouts allow discharge into the different duck wetlands in Suisun Marsh. FSSD reports that approximately 10% of their flow is recycled for agricultural use.

Flow to the wetlands from FSSD is officially managed by the SRCD, though wetland owners oftentimes are allowed to operate the turnouts. The FSSD began keeping records of water discharged to Wetland 112 in the summer of 2008. Record keeping at Wetland 123 began in the summer of 2009, so no data are available for the study period. Wetland 112 receives an average of 75 ac-ft per month though that amount varies greatly (Table 7). On average, about 5% of the discharge from FSSD goes directly onto Wetland 112. During 2008, the wetland received as little as no water to as high as 235 ac-ft. During the fall of 2008, flows into Wetland 112 had monthly averages of 4 – 8 ac-ft/d (2 – 4 cfs) and were about 10 – 16% of the total flows from FSSD. Using an estimated 13% diverted flow from FSSD during the Fall 2008, approximately 5 – 6 ac-ft/d (2.5 – 3 cfs) of flow from FSSD was diverted to Wetland 112 during the Fall 2007. During Fall 2007, an average of 4 inches of water (66 ac-ft) for a daily average of about 9.5 ac-ft. From this analyses, the water from FSSD provides on average about two thirds of the weekly averaged water demand.

Discussion

Wetland Management

Landowners in Suisun Marsh utilize mechanical and hydrologic cultural practices to actively manage the vegetation community in their wetlands in order to achieve a beneficial food source for wetland dependant wildlife, control nuisance invasive vegetation, and reduce potential impacts to water quality. Mechanical techniques primarily include mowing, disking, and herbicidal treatments, which are employed to reduce the presence of unwanted or invasive vegetation and reduce vegetative ground cover. Water management involves a series of flood-drain cycles timed throughout the year to reduce soil salinities, and encourage the establishment of a plant community that is beneficial to wetland dependant wildlife.

Maintaining low soil salinities in the managed wetlands is a high priority. If the soils become too salty, salt tolerant plants are encouraged to invade which are perceived to provide less value to wildlife than fresh water wetland plants. While the wetlands are flooded for the migratory waterfowl use, water is circulated throughout the wetland to keep salinities as low as possible. In the winter and early spring, following waterfowl hunting season, a series of 2-3 flood-drain cycles are usually performed to flush accumulated salts from the soils, taking advantage of reduced water salinity in Suisun Marsh during that time of year. In the summer, the wetlands are normally drained for a period of 1-3 months so that landowners can perform other maintenance activities on the wetlands. This dry period also allows wetland plants to seed and sprout. The entire years work, leaching, circulating, mowing, disking, and other maintenance is done so that the wetland plants will provide food, in the form of seed, and cover not only for waterfowl and other wildlife but also for aquatic inverts which are also used as a food source.

Overlain upon these established management practices have been recommended practices to reduce water quality impacts in general and specifically low Dissolved Oxygen effects in sloughs that have occurred from wetland management activities. In this study, hydrologic recommendations were made to reduce fall wetland discharges through limiting the pre-flood cycle to a brief wetting of the marsh plain, followed by an instant drawdown that leaves the marsh plain dry for at least seven days. This recommendation was successfully implemented at both wetlands to some extent as shown in Figure 9 and Figure 10 with both wetlands showing extended low water level elevations during the initial flood-drain-flood period. However, the goal to reduce fall wetland discharges was not very successful as second year flood and discharge volumes were larger during the second year than during the first year (Table 4). This higher discharge during the second fall occurred for two reasons: 1) water was flooded to a higher elevation and 2) water was drained longer and to a lower elevation. These two actions resulted in more complete marsh flooding and draining.

Thus, though landowners successfully implemented specific cultural practices, their actions did not meet the overall hydrologic goals. Several factors complicate water management implementation:

- Tidally fed systems are complicated and difficult to manage precisely given the available infrastructure, the dynamic nature of the tides, and the tidal differences from year to year;
- Reducing hydrologic volumes on and off the marsh run counter to goals of managing salinity and maximizing water exchange throughout the marsh and no value for the landowners in this modified management has been determined for the landowners;
- No real time hydrologic measurements are recorded to provide feedback on hydrologic practices; and
- Specifications and requirements need to be precise

These factors challenge the sustainability of cultural practices to manage wetland hydrology to reduce water quality impacts, especially when those changes increase the difficulty to manage in ways perceived to optimize waterfowl habitat.

Tidal Effects Minimize Evapotranspiration and Precipitation Contributions

The managed wetlands are tidally dominated systems and these tides generally overwhelm climate effects. This result especially applies to evapotranspiration, which from early fall through late spring typically ranges from 0.5 to 0.8 inches per week (Figure 16). This hydrologic loss is an order of magnitude less then tidal losses from the wetlands (Figure 14).

Precipitation is patchy, occurring during this study mostly from December 2007 through Feburary 2008. Over half the weeks during that period had precipitation over 0.5 inches per week. Precipitation during that period ranged from about 0.5 to 2.0 inches per week (Figure 16). In all, about 8 inches of rain fell. In comparison, tidal exchange resulted in 4 – 11 inches per week at Wetland 123 and 3 – 8 inches per week at Wetland 112. About 60 inches of water in total was applied tidally on Wetland 112 from December 2007 through February 2008 and about 95 for Wetland 123. Thus, in total 8 to 12 times the amount water was introduced onto the wetlands through irrigation from tidal exchange (or treated wastewater) than from precipitation.

Characterizing Hydrologic Effects on Water Quality

The hydrology within the wetlands is characterized by short term tidal exchanges (Figure 9, Figure 10) and by longer term spring-neap cycles (Figure 8). These cycles result in tidal exchange onto and off the wetlands during each tide event (Figure 13). During the flood periods, water volume increases by about 20 – 120% during each tidal cycle (Figure 15). However, during the remainder of the fall, only about 5% of the water is added during each tidal cycle.

Figure 17 models the change in the concentration of a hypothetical tracer in the marsh water column versus the number of tidal exchanges. This simple model assumes the marsh plain is relatively well mixed and diffusion dominated. Water is applied and discharged in batches with water being added and removed uniformly across the marsh plain.

Depending upon the amount of water as a percent of the initial water volume, a different number of tidal cycles are required to flush the tracer from the system. Under periods of flooding during which 50 – 100% additional water is added onto the field during each tidal cycle, the predicted tracer concentration changes in the water column greatly. Under conditions in which water volume in the marsh increases by 100%, the tracer concentration is halved after two cycles and is one tenth after about 4 tidal cycles. However, during much of the fall as discussed above, only around 5% of new water is added. (The median exchange for the data set was 7%). Based upon the 25^{th} – 75^{th} quartile range, about 3 to 15% of the water is exchanged during most tidal cycles for periods during which water levels are maintained. Thus, the HRT for export of 50% of that water is estimated to be 6 – 23 tidal cycles, and for 90% of that water to be 18 – 78 days.

This model suggests large changes in water column in the short-term within the marsh plane are not driven by hydrologic exchange but by other factors such as biogeochemistry.

Fall and Spring Flood and Drain Events in Context of Slough System

The water budget shows flood and drain events occurring in the fall are similar in magnitude to those occurring in the spring (Table 4). This result shows true for both wetlands. At Wetland 123, flood events during the fall have higher calculated flow rates onto the wetlands then those occurring in the spring. However, discharge rates for the drain events are similar. Moreover, the water volumes exchanged during the spring and fall are in the same range of 160 to 350 ac-ft. At Wetland 112, the fall and spring events have similar flow rates. Water volumes exchanged range from about 35 – 113 ac-ft.

However, there are several caveats with this observation. First, the fall flood events unlike the winter flood events require the soils become saturated. Saturation requires somewhere in the range of 2 -12 inches depending upon the soil types, the depth to the water table, the antecedent moisture content at time of flooding, etc... For these two wetlands, we estimated approximately 110 – 125 ac-ft was required to saturate the soils. S

Second, though the events are similar in magnitude, the number of events is greater in the spring. At Wetland 123, one drain event occurs during each fall and three drain events occur during the spring. (Note the last drain event in which the fields are drained for summer field work is not shown). At Wetland 112, one drain event occurs during each fall. However, in the spring four drain events occur.

Finally, the on wetland actions need to be considered in the context of the slough system. Enright (2009) describes the flows in Boynton and Peytonia Slough. He estimated net upstream flows from mid October to early December of around 0 to 80 cfs in Boynton Slough and flows varying from about 50 cfs in the downstream direction to 50 cfs in the upstream direction along Peytonia Slough. This fall period is the longest period of upstream flow for the year and distinctly different from the subsequent winter and early spring periods. The winter periods sees some short upstream flow spikes but also periods of elevated flow in the downstream direction greater than 50 cfs. By spring, net flow has decreased to about 10 – 20 cfs but is still generally in the downstream direction.

The long period of reverse (upstream) flow in the fall is likely due to several factors. The preceding summer periods also experience reverse flow along Boynton with flow varying from about 20 cfs in the downstream direction to 50 cfs in the upstream direction (2008 data). However, the reverse flow increases dramatically in the fall with the filling of the duck wetlands and this demand is not only to raise the water levels in the wetlands but also to saturate the soils. The requirement to saturate the soils greatly increases the water demand during the initial flooding periods by about 70 – 200% depending upon the wetland and its operation (

Table 3, Table 4, Table 8).

The flow in the sloughs during the winter also has implications on wetland management. Flows from January through end of March are elevated and strongly in the downstream direction. Though the wetlands have several drain-flood events during this period and those events are oftentimes extreme, their effect on flow is not apparent when compared to the slough data. These results suggest that because net slough flows are greater in magnitude and nearly always in the downstream direction, wetland management activities within the marshes affect the hydrology of the slough system less in the winter than during the early fall.

Water Wetland Demands

Wetlands take a lot of water during flooding and release a lot of water when draining. According to the IEP (2007), Suisun Marsh contains 52,000 acres of managed wetlands, many of which are managed for waterfowl habitat. The total water demand is unclear for this area. Based upon the data here, we estimate soil water demand to saturate the soils to be in the range from 2 – 12 inches. Surface waters were raised in this study 4 – 8 inches across the duck wetlands. Water control structures are primitive and flow on and off the wetlands cannot be easily measured. What are the water demands of these wetlands and how do those demands impact the sloughs?

Table 9 estimates the demand from the Suisun managed wetlands based upon above estimates. We estimate 17,000 to 87,000 ac-ft is required during fall flooding. An average of these values is about 56,000 ac-ft, or approximately 1 foot per ac-ft of managed wetland.

Conclusion

Two managed wetlands, Wetlands 112 and 123, were studied in Suisun Marsh to better understand the hydrology of managed wetlands in the context of the surrounding Suisun Marsh. Beginning in late September, these two managed wetlands are flooded, drained and reflooded again. Water levels are then maintained relatively constant under quasi-steady state conditions until around February where the wetlands are drained and reflooded two or three times until a final drainage period near May. Wetland 123 receives water from two sloughs: Boynton Slough from the south and Peytonia Slough from the north as well as the FSSD wastewater treatment plant. Wetland 112 receives water from Peytonia Slough from the north and from the FSSD wastewater treatment plant.

The hydrology of these two wetlands are tidally dominated. Evaporation minimally affects water budgets with tidal losses one to two orders of magnitude greater. Precipitation events can be relatively large but seasonally precipitation inputs are about one order of magnitude less then tidal inputs.

The wetlands are flooded and drained to optimize migratory waterfowl habitat. Water from management of water control structures along the perimeter control the rate tidal water enters each wetland. Additionally in both wetlands, FSSD turnouts are managed by SCRD to provide tertiary treated wastewater from FSSD. During the Fall, Wetland 112 receives an estimated 2 – 4 cfs from FSSD or about 4 – 8 ac-ft/d. About 3 to 8 inches of water are put on Wetland 112 each week (7 – 19 ac-ft/d) so the water from FSSD is potentially about half the water demand at Wetland 112.

During flooding of the wetlands, water levels in the wetlands are raised to about the same elevations from early September through April. Water levels are raised to about 5.75 +/- 0.25 ft-NAVD at Wetland 112 and about 4.0 +/- 0.25 ft-NAVD at Wetland 123. Thus, these flood events throughout the year have similar amounts of surface water exchange.

These flood and drain events are the most significant hydrologic events for these wetlands. Over a period of a week, average water volume increases by tide range from 20 – 80% but can be over 100%. And drain events typically decrease water volumes by 20 to 40%. These results are in contrast to the period of quasi-steady state operation where water volumes change on the order of +/- 5%.

The distinctly different hydrologic periods will result in different hydrologic characteristics in the wetlands. During flood and drain periods, water imports and exports are dramatic across the marsh and whether one is in the marsh plain or along a wetland ditch, water characteristics will change relatively rapidly. Along the ditches, preferential flow paths will be formed and water will move rapidly over at certain times of the tidal cycle. Within the marsh plain, rapid changes in water level will result in relatively short HRTs of a few hours to a few days. However, during the quasi-steady state period, the hydrology in the wetland is expected to differ greatly between along ditches as compared to in the marsh plain. Near ditches, preferential flow paths are still expected and water chemistry will likely change rapidly. However, in the marsh plain, the relatively small changes in water level and the minimal dilution will result in very long HRTs on the order of many days to a couple weeks.

During single flood events, several hundreds of acre-feet of surface water floods these wetlands. Wetland 112 has 35 to 113 acre-feet of water flooded onto it. Wetland 123 has 170 to 360 acre-feet flood onto it. Drain events are of similar magnitude.

In addition to the surface water addition, these wetlands experience saturation of their soils. This fact is especially critical during the first fall flood event during which soil properties indicate the soils become saturated in less than a week. Soils are very porous and have approximately 20 – 25% of their pore space available for saturation. Thus, the soil data predicts 4 – 8 inches of water is required to saturate the soils and given the uncertainty we broaden the range to 2 – 11 inches. Regardless, these numbers translate to large volumes of water needed to saturate the soils during the first flood event. 100 – 125 ac-ft are predicted as the water volume needed to saturate each wetland.

The hydrologic management of the wetlands impacts the surrounding sloughs most greatly during the fall. At that time of the year, the sloughs experience reverse flow and depressed DO levels. Reverse flow is likely a combination of minimal riverine runoff in this Mediterranean climate as well as the water demand from the managed wetlands in Suisun Marsh. Based upon our analyses here, we estimate 56,000 ac-ft are required to saturate the soils and flood the wetlands at the beginning of fall in preparation of duck season.

During the winter and spring, flood and drain events at the slough are less problematic. Soils are already saturated so minimal water is needed for that purpose during drain-flood events.

Moreover, winter and spring flows in the surrounding sloughs are generally in the downstream direction. Winter flows are of a much larger magnitude then fall flows. Given all these factors, the impacts from wetland management on the slough hydrology are much less during the winter and spring than the fall.

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Figures

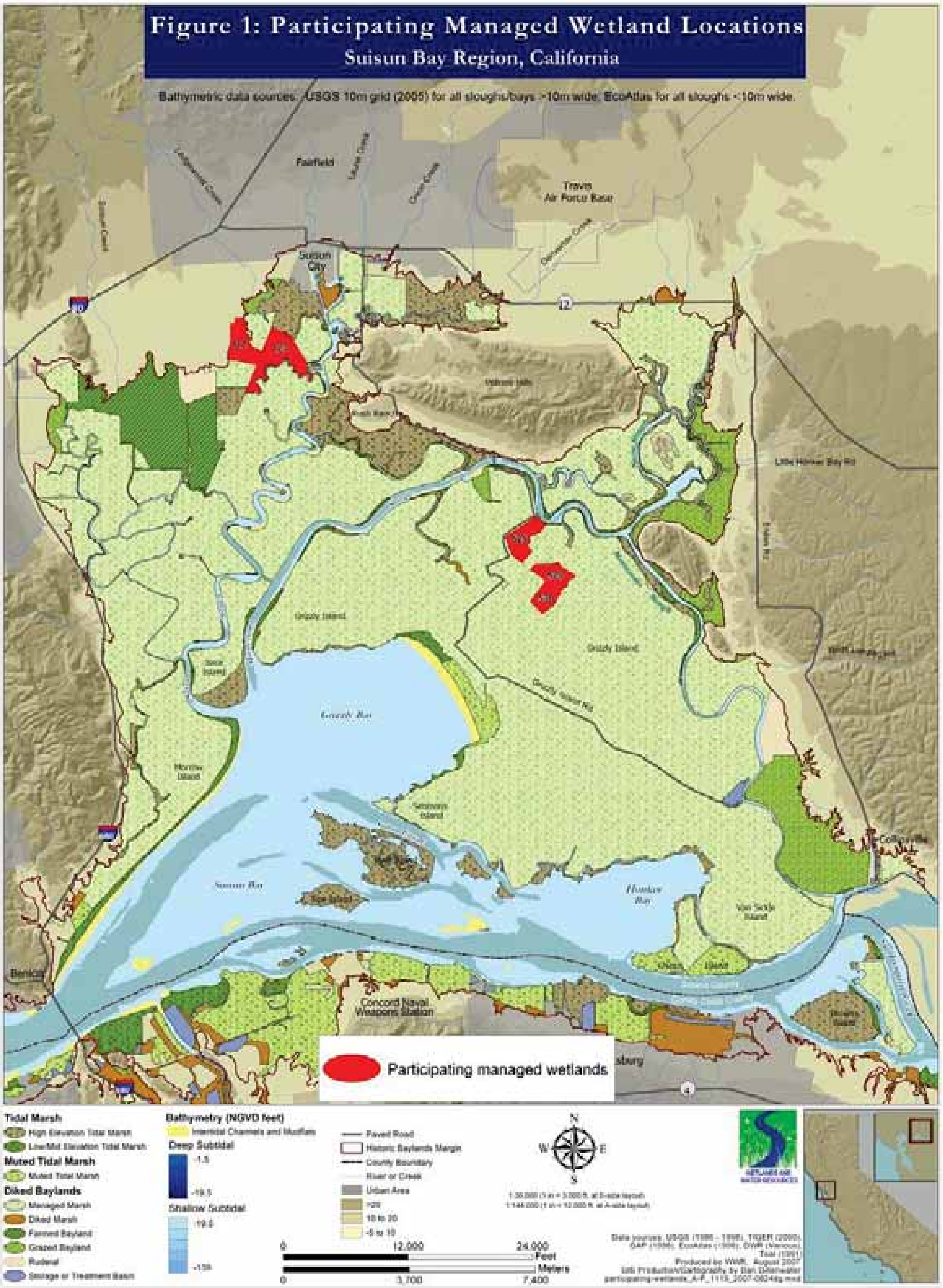


Figure 1. **Map of Suisun Wetlands and Identification of Sites**

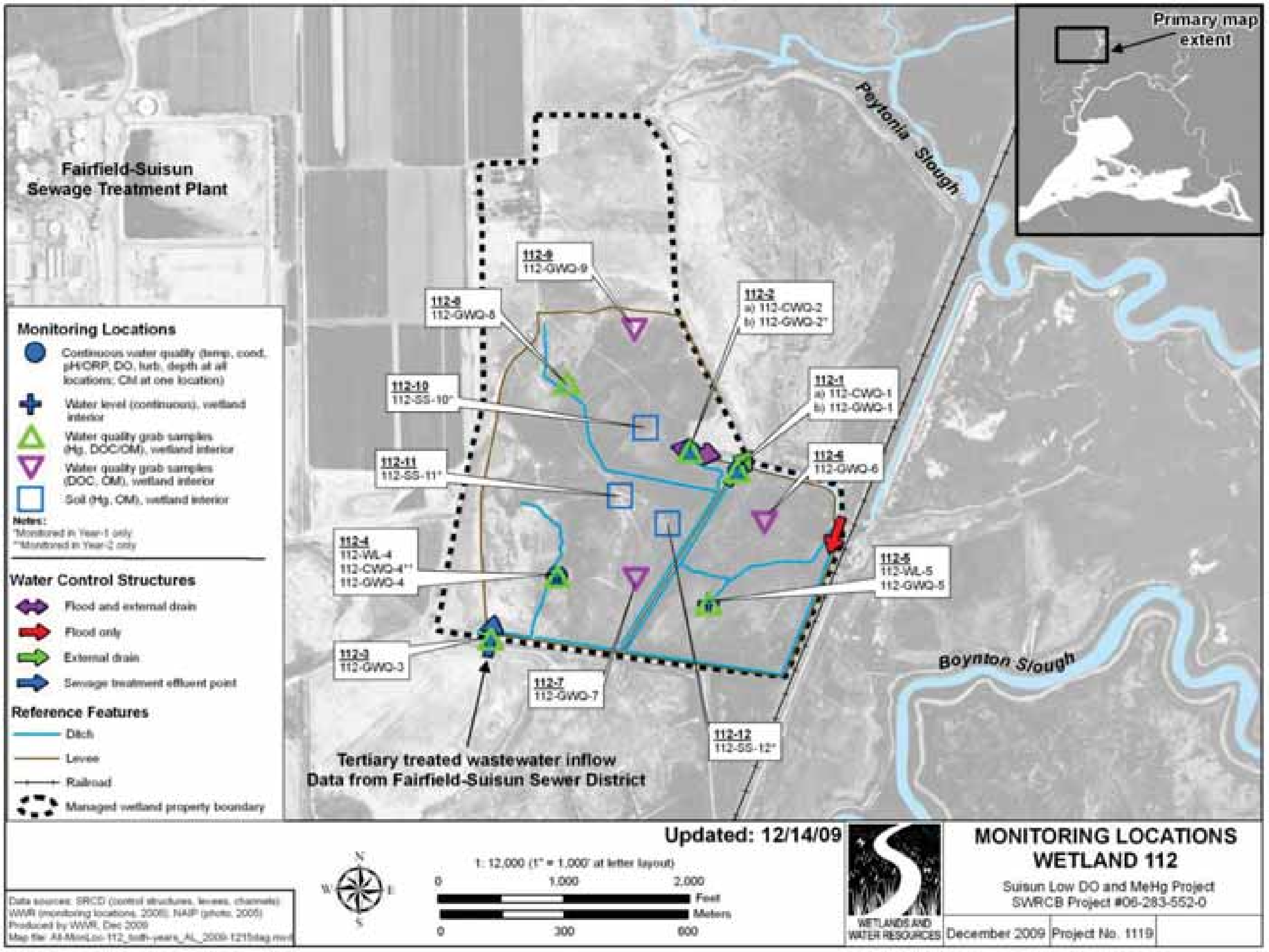


Figure 2. Wetland 112

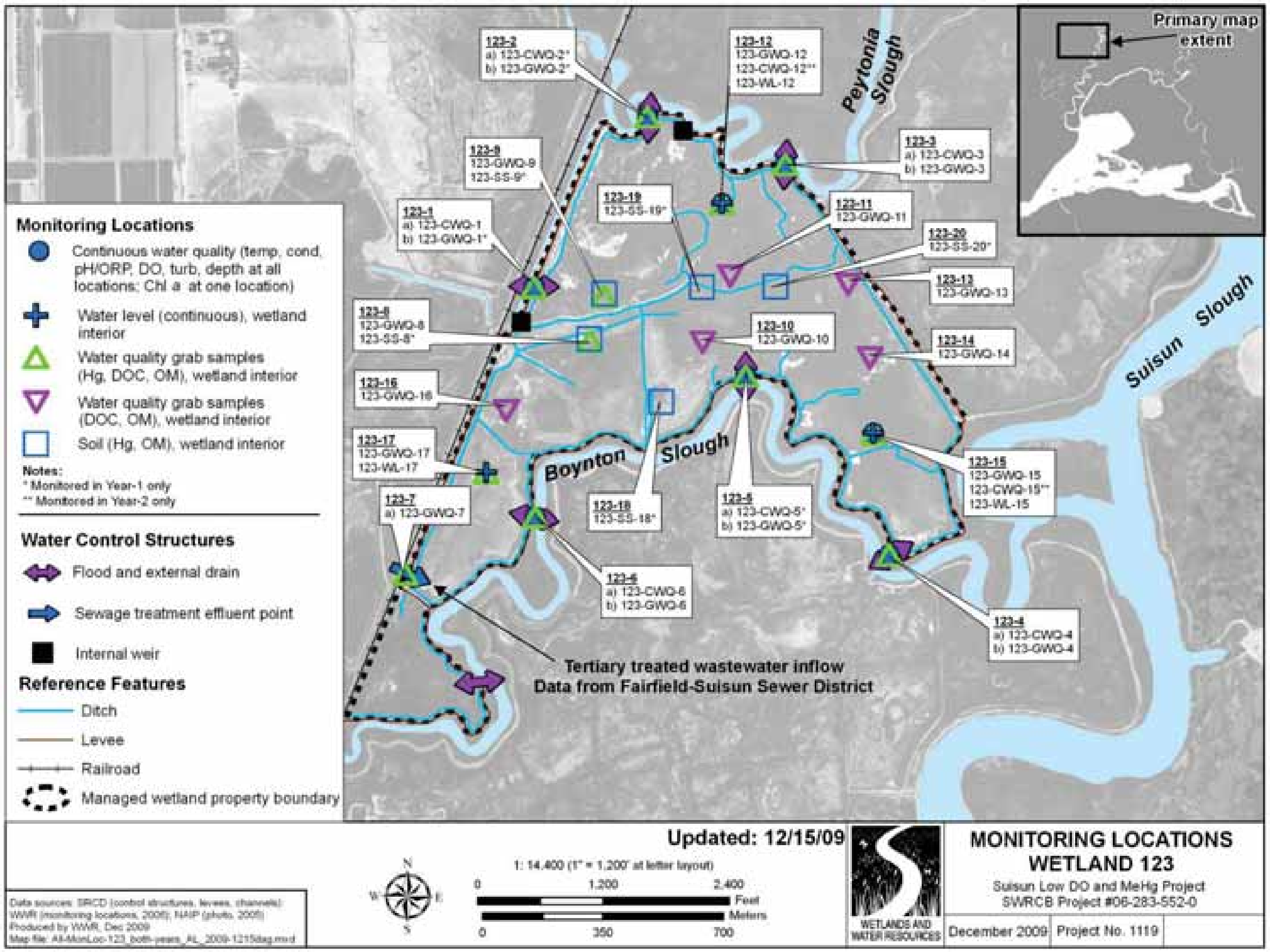


Figure 3. Wetland 123

Figure 4a. Marsh Plain Installation Stilling Well (Pressure Transducer Only)

Figure 4b. Marsh Perimeter Installation Water Control Structure Stilling Well (Multi-parameter data sonde)

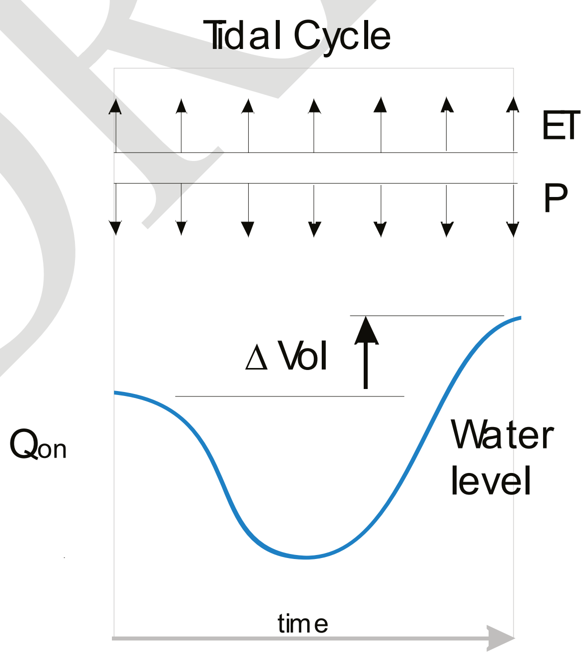


Figure 5. Water Balance Model

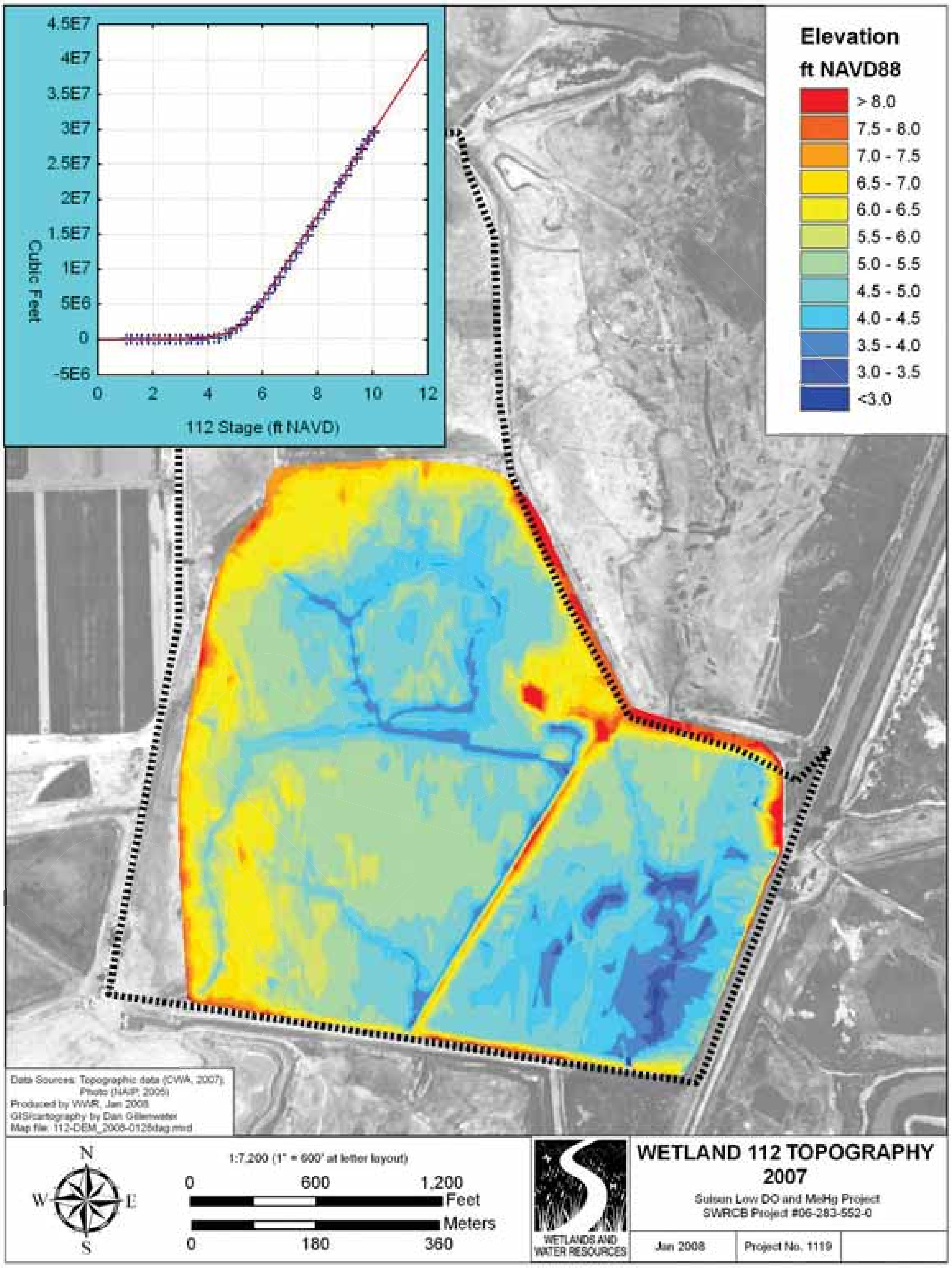


Figure 4. Club 112 Digital Elevation Map with Tidal Volume vs Elevation Relationship

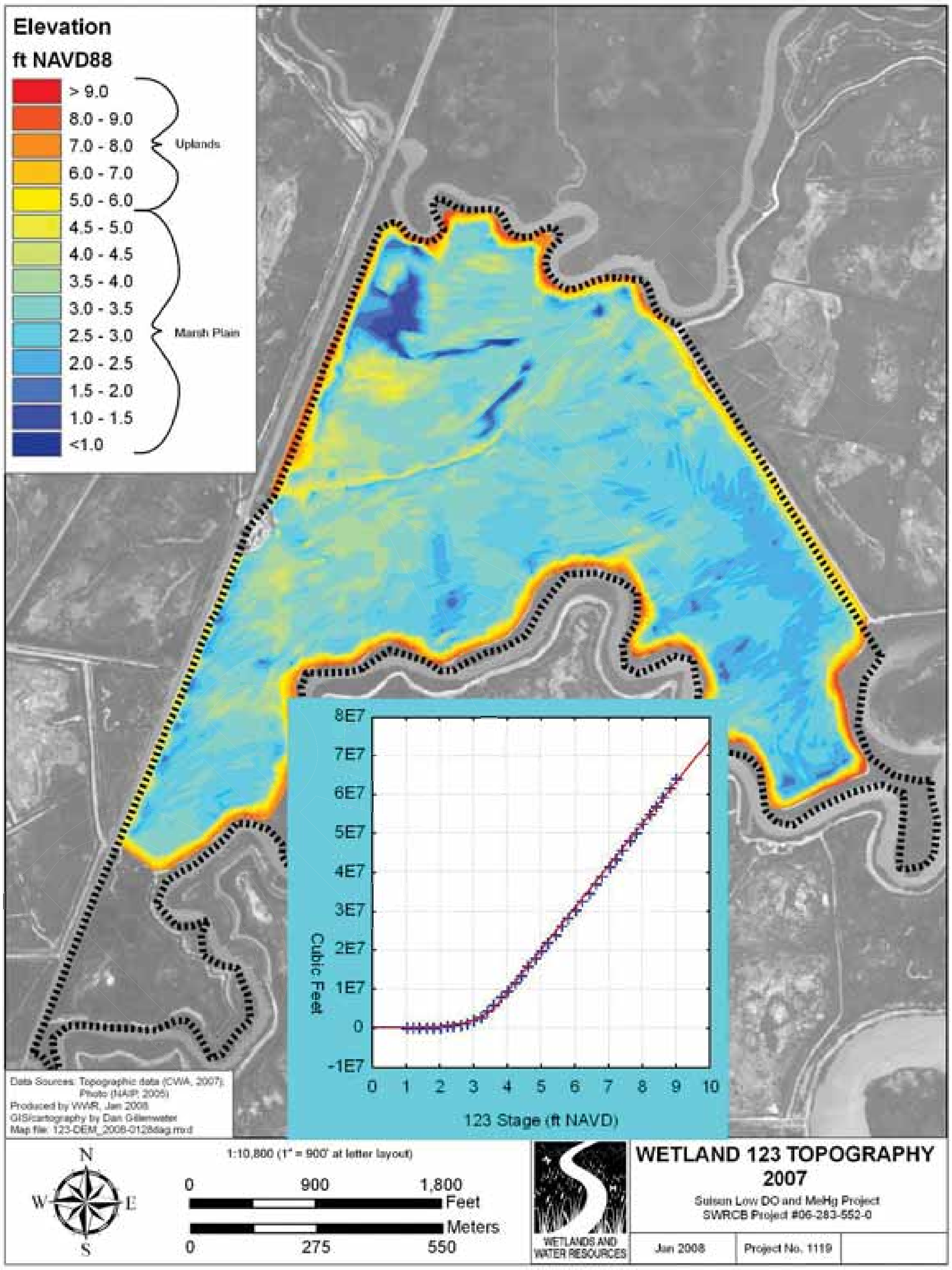
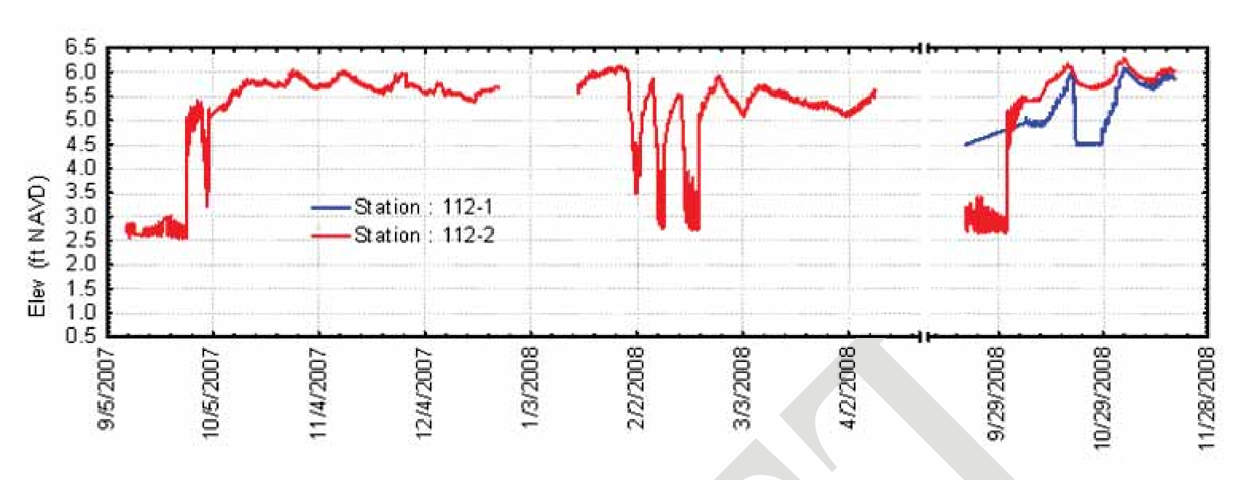
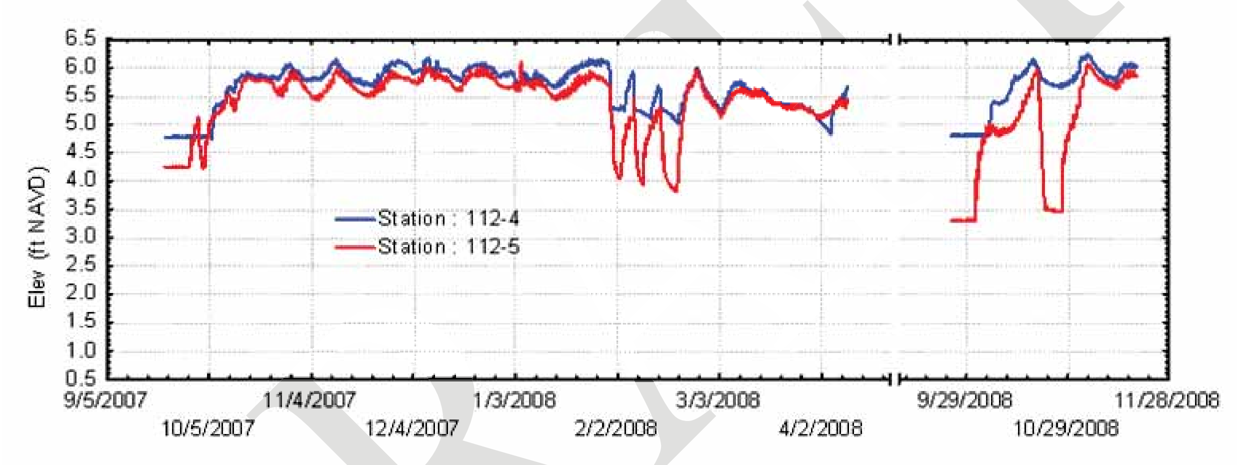


Figure 5. Club 123 Digital Elevation Map with Tidal Volume vs Elevation Relationship



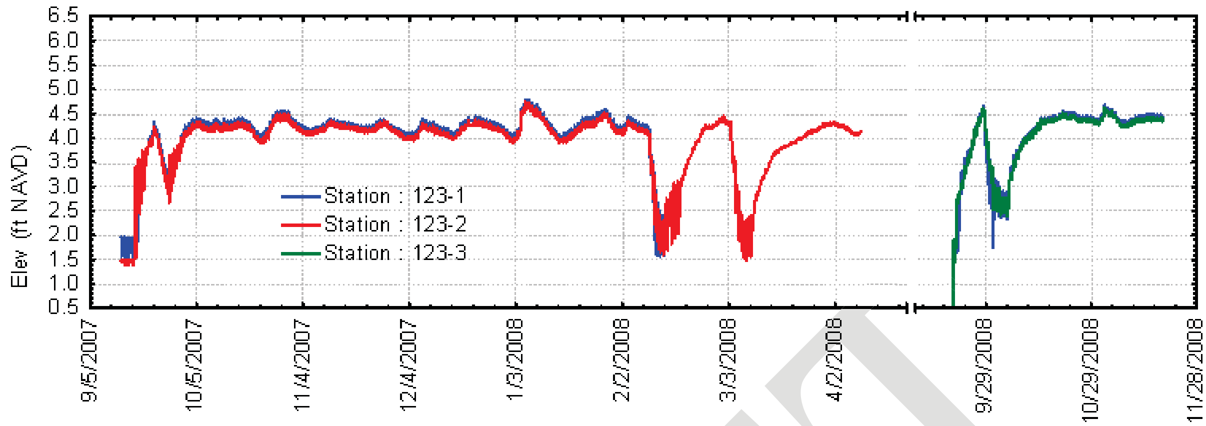
A. Perimeter Sites



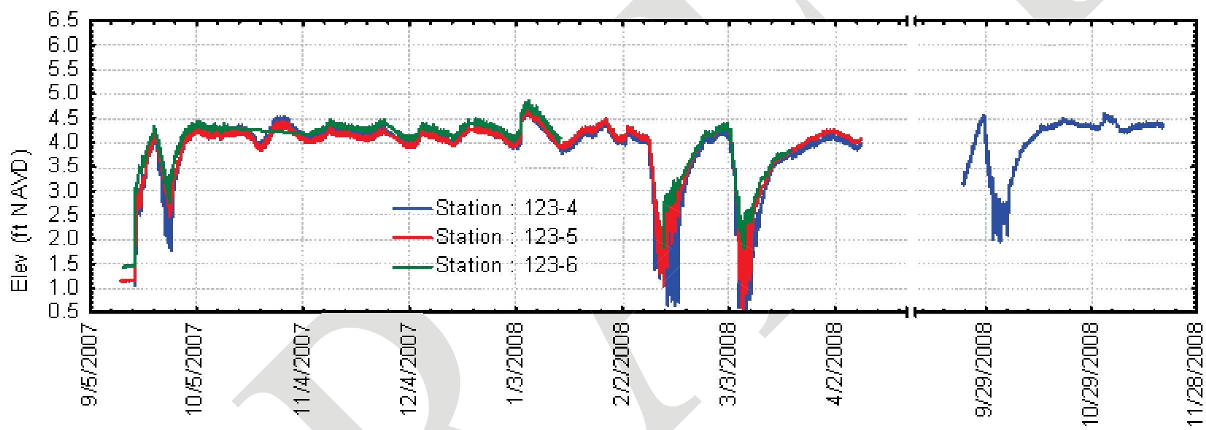
B. Internal Sites

Figure 6. Tidal record at Club 112: External and Internal Sites.

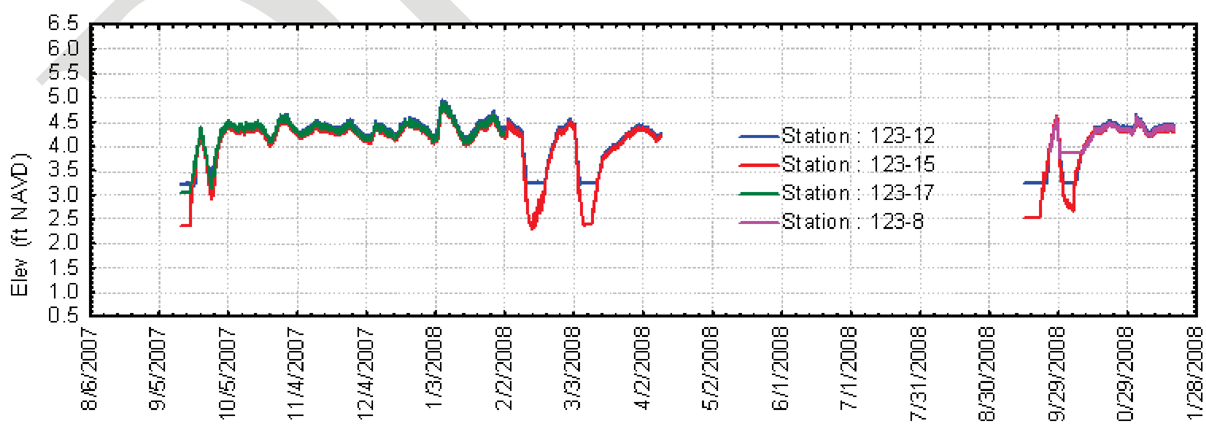
Club 123



A. Northern Perimeter Sites

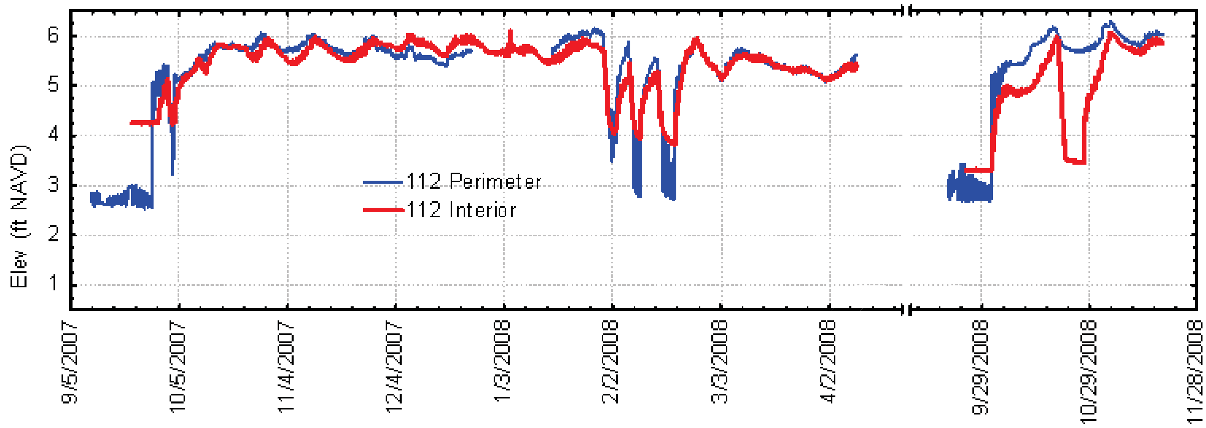


B. Southern Perimeter Sites

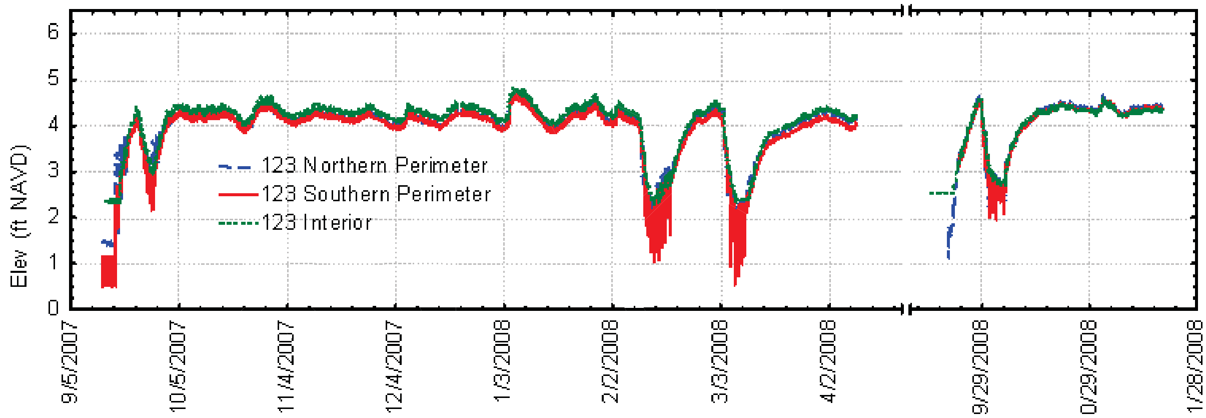


C. Internal Sites

Figure 7. Tidal record at Club 123: External and Internal Sites

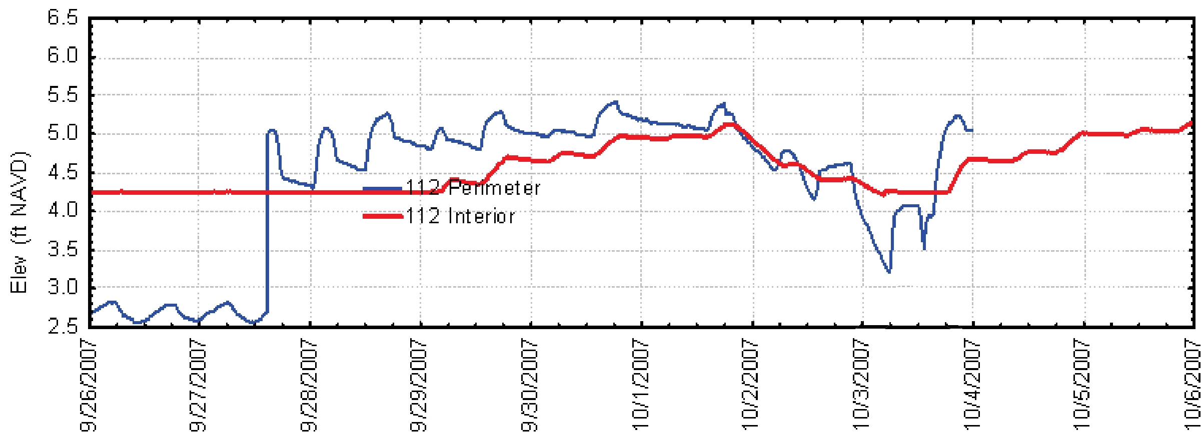


A. Club 112

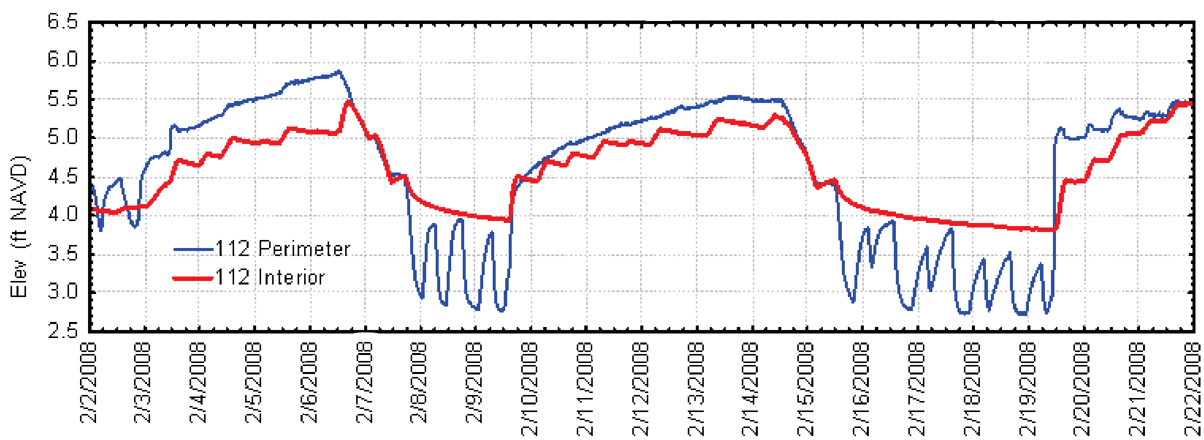


B. Club 123

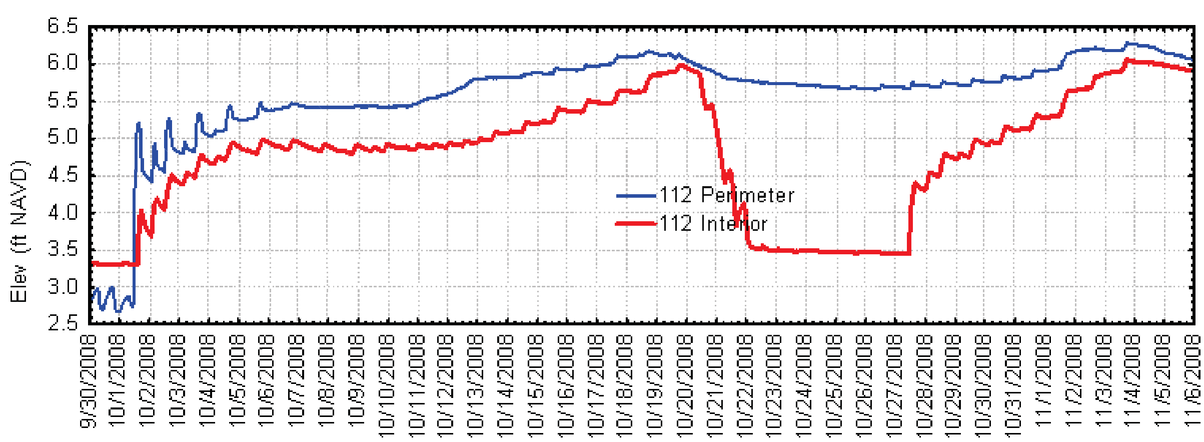
Figure 8. Regional Trends at Club 112 and 123.



A. Fall Year 1

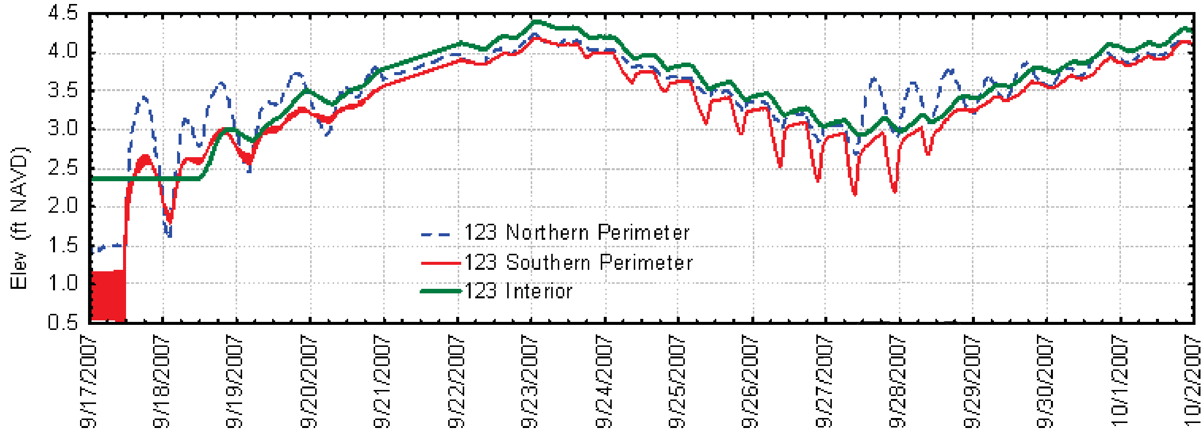


B. Spring Year 1

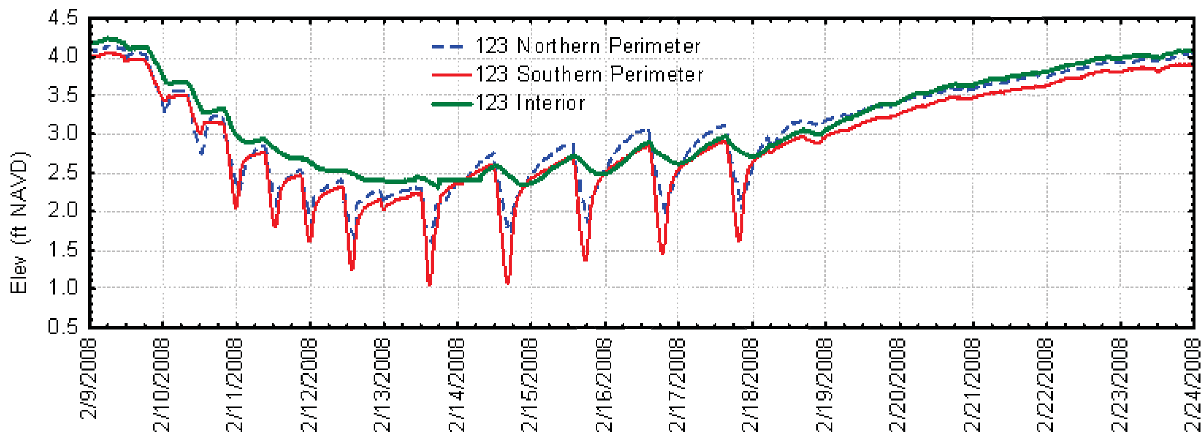


C. Fall Year 2

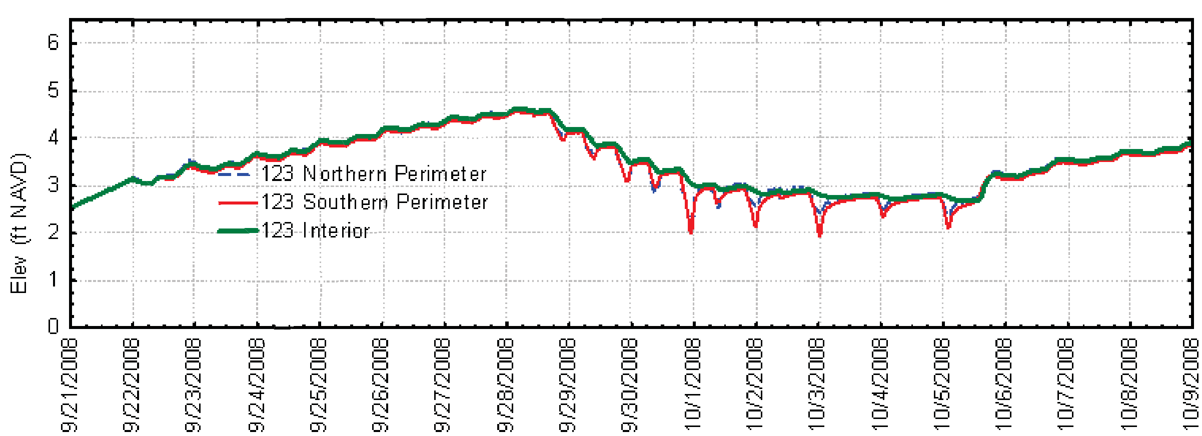
Figure 9. Club 112 Draining and Flooding Cycles during Year 1 and Year 2 during fall and spring.



A. Fall Year 1



B. Spring Year 1



C. Fall Year 2

Figure 10. Club 123 Draining and Flooding Cycles during Year 1 and Year 2 during fall and spring.

Temporal ET and Precipitation Records

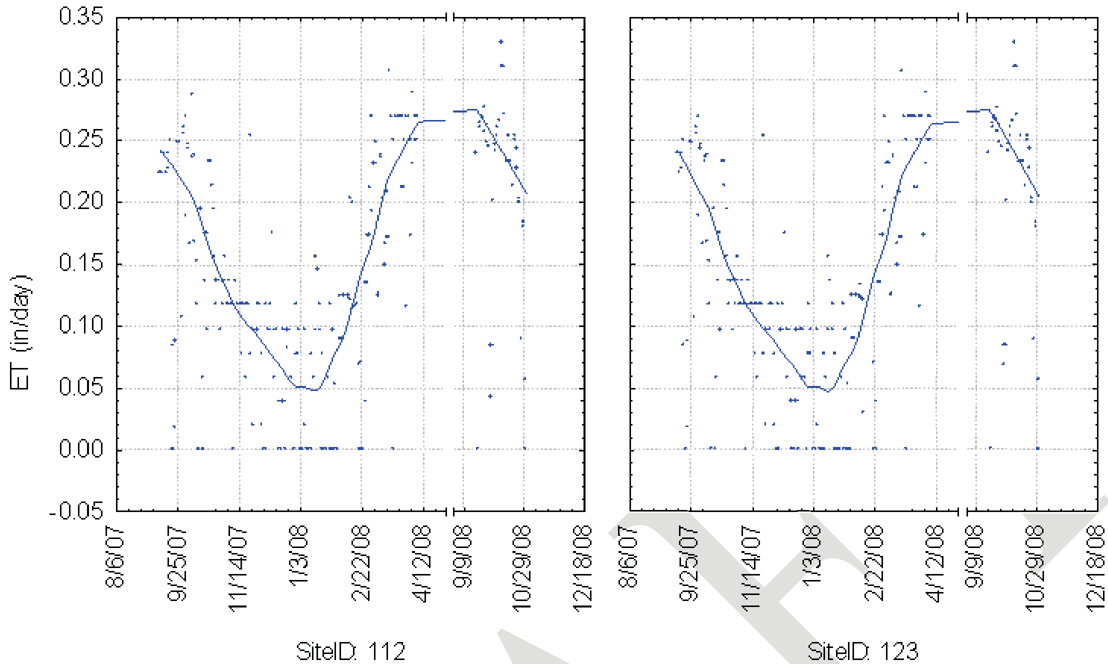


Figure 11. Temporal Changes in ET (in/day) at site.

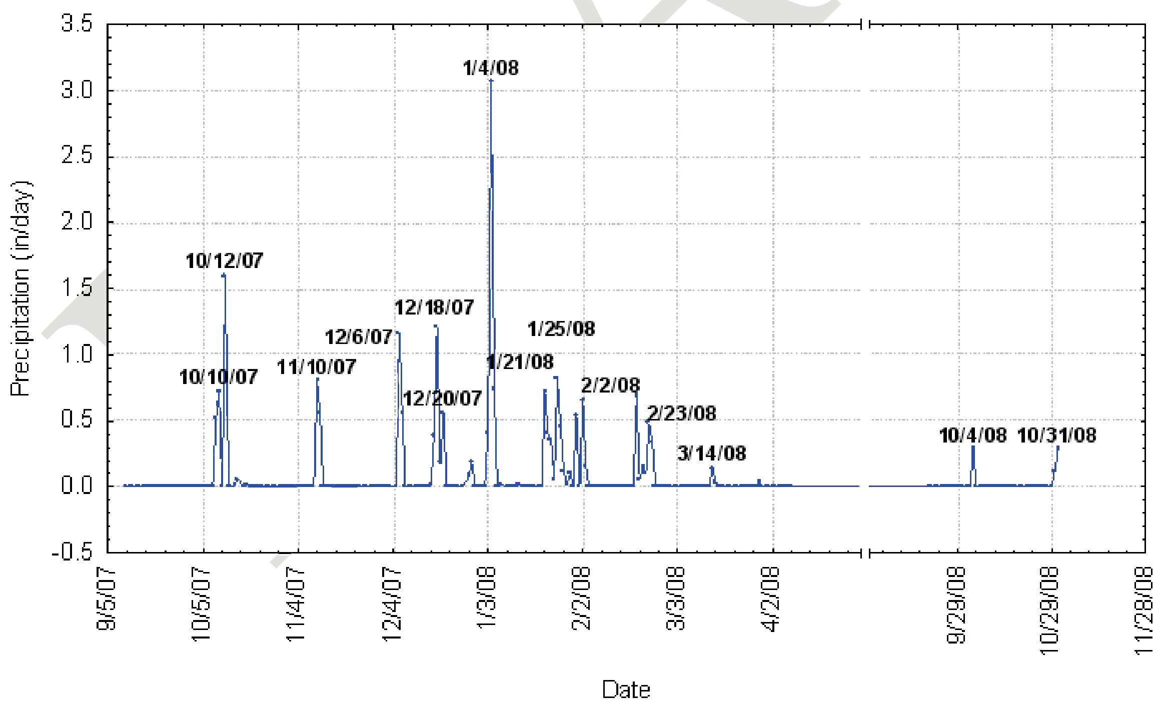
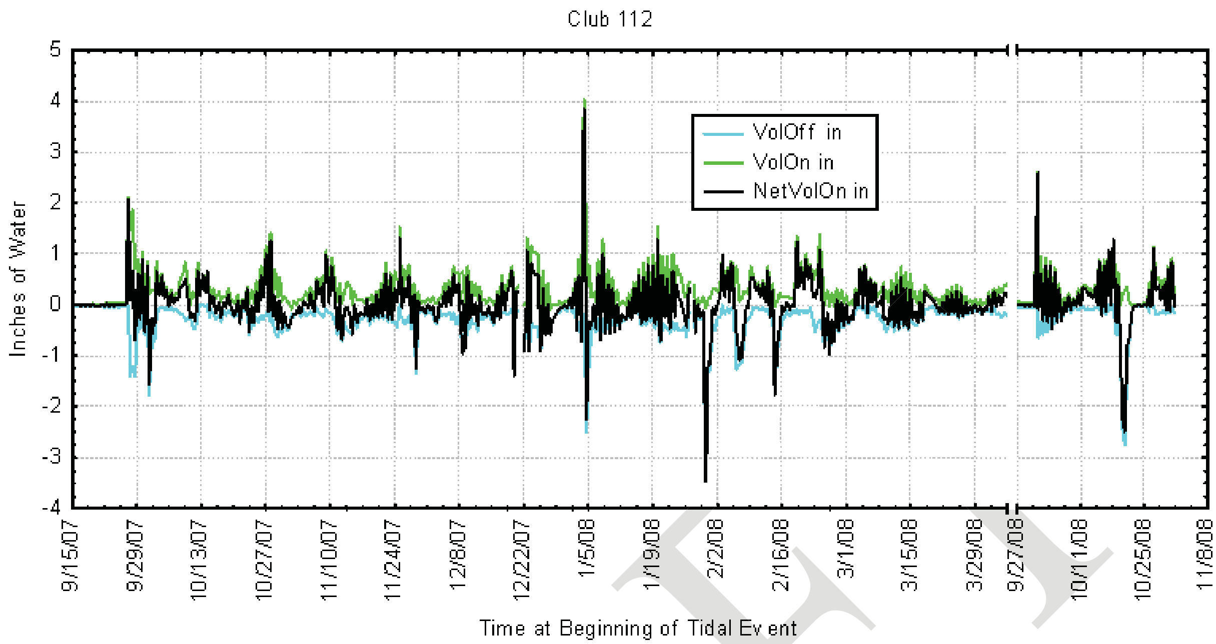
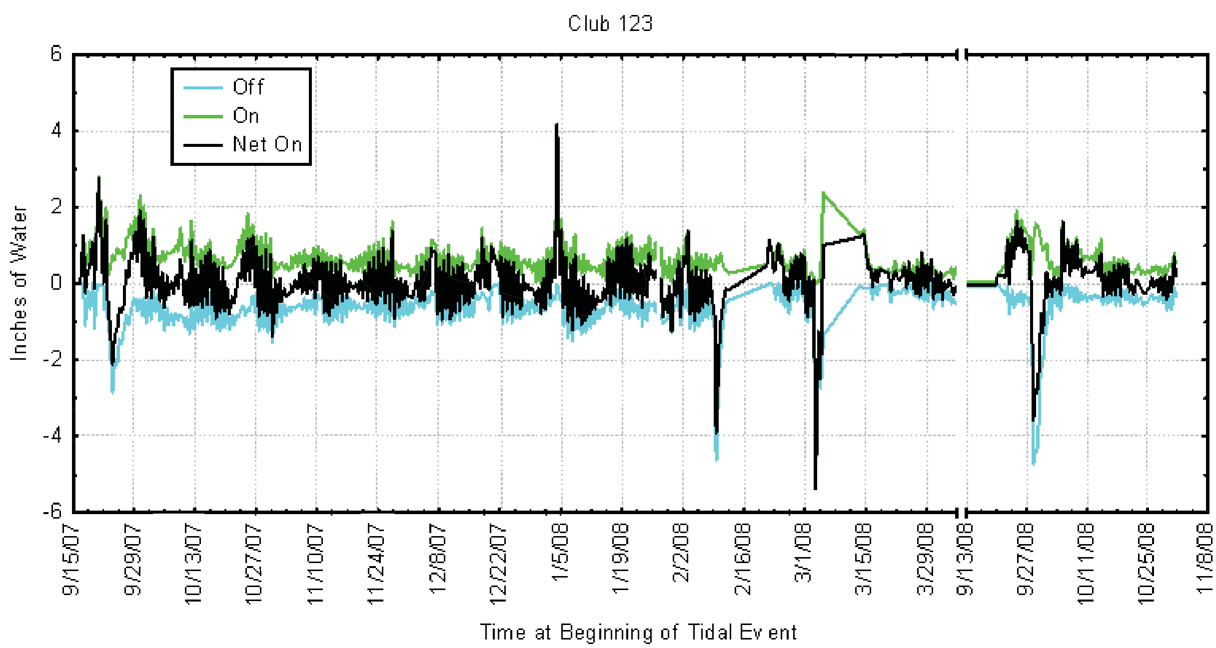


Figure 12. Precipitation Events

Events over 0.5 inches are labeled for the first sampling year. All events are labeled for the second sampling year.



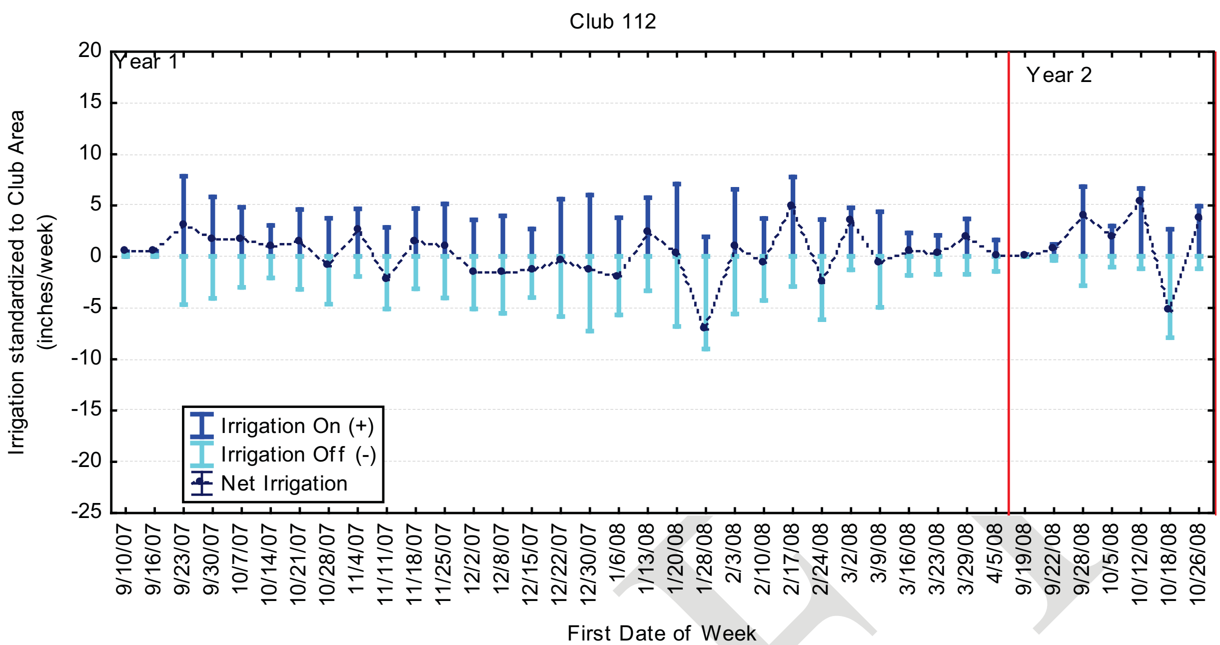
A. Club 112



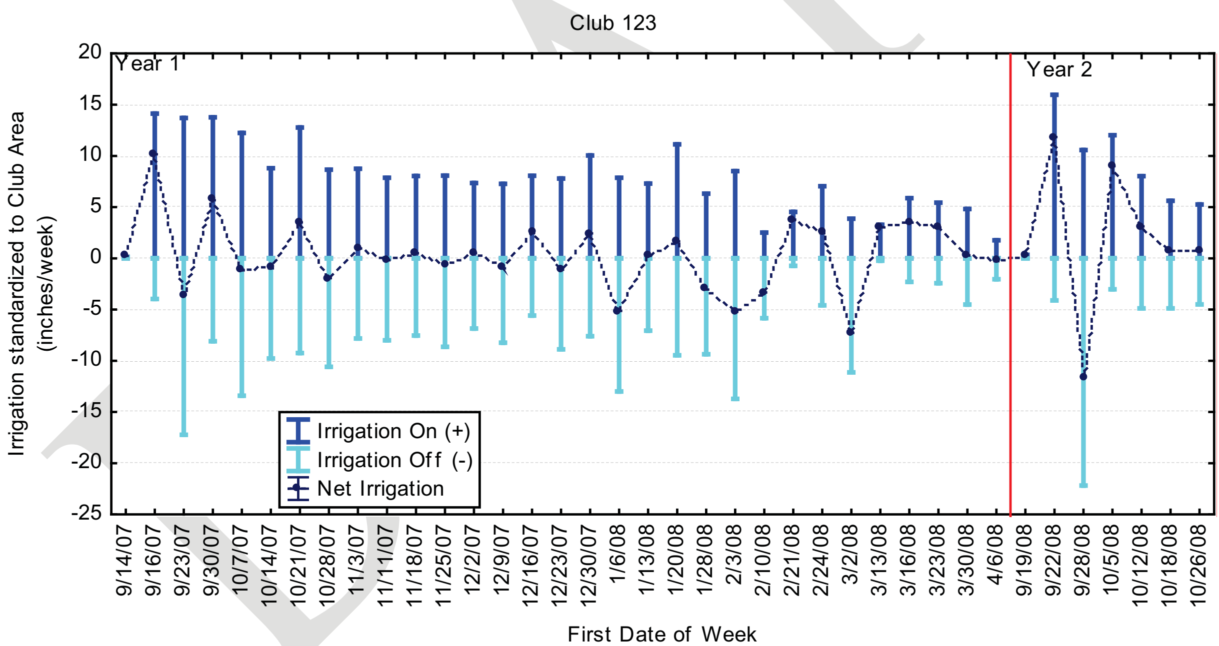
B. Club 123

Figure 13. Surface Water Exchange by Date

The net surface water exchanged represents the difference between the calculated surface water applied and discharged by tidal cycle. Positive values equal water onto the club and negative values equal water off the club. Volumes on and off are calculated by tide based upon high and low tide elevations as measured within the clubs.

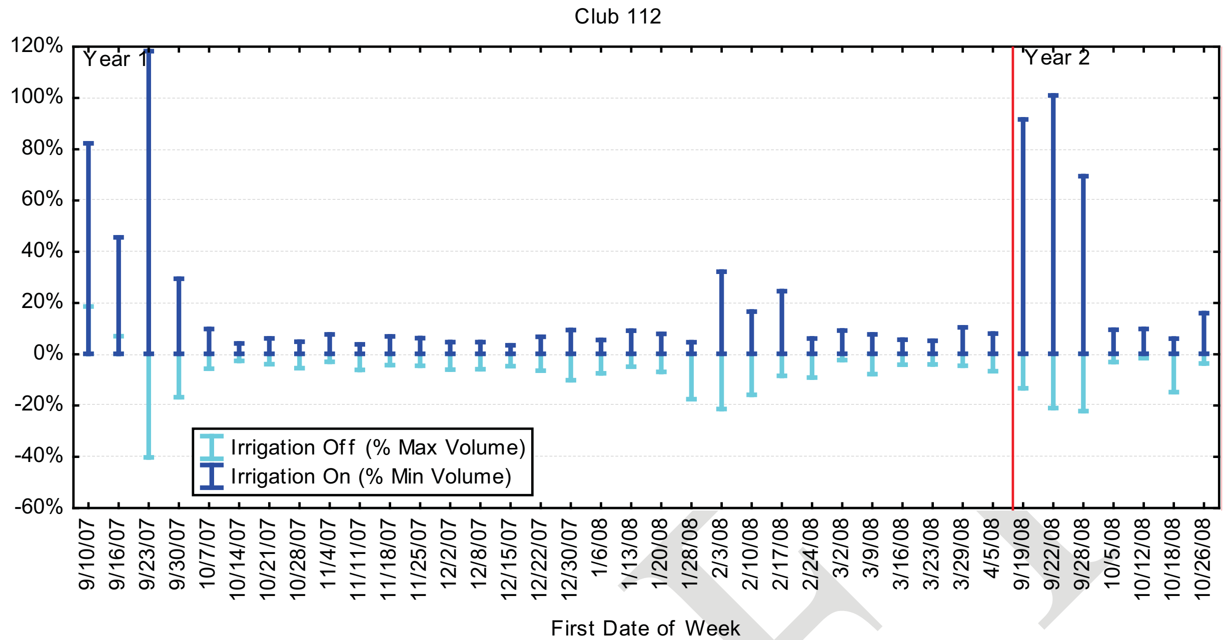


A. Club 112

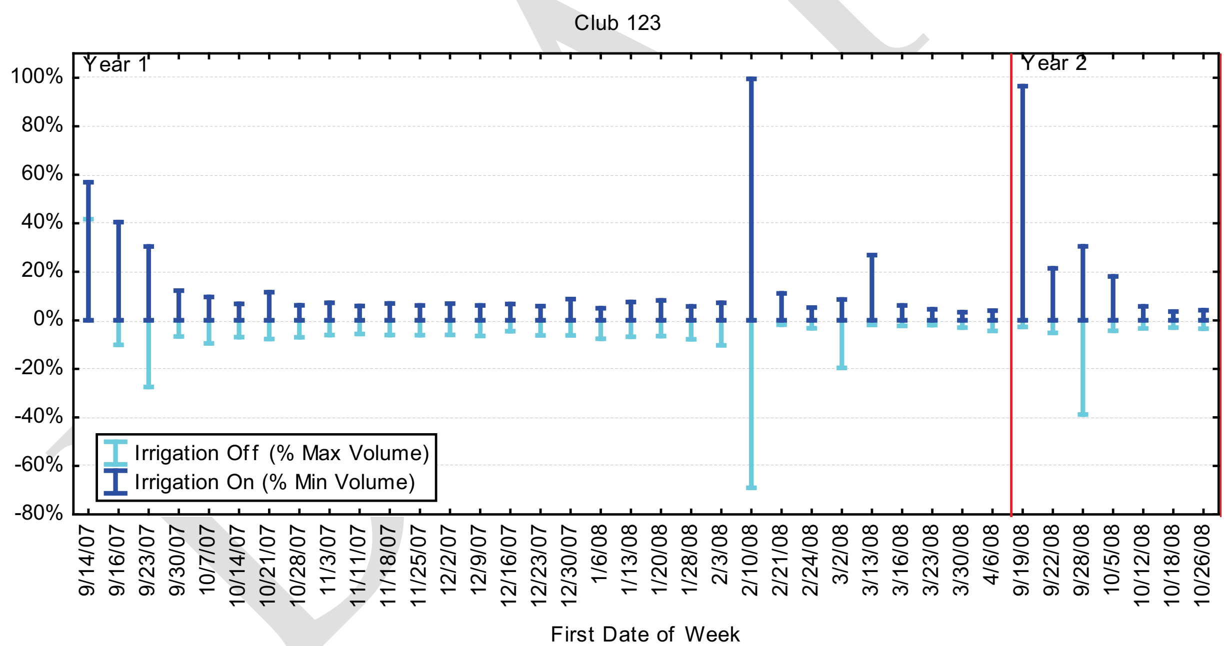


B. Club 123

Figure 14. Weekly Surface Irrigation Water On, Off and Net.
Figure shows the total surface water applied and discharged from the clubs during the first and second years, and the net water applied (applied – discharged). Hydrologic data is standardize to club area and water volumes applied and discharged are in inches per week.

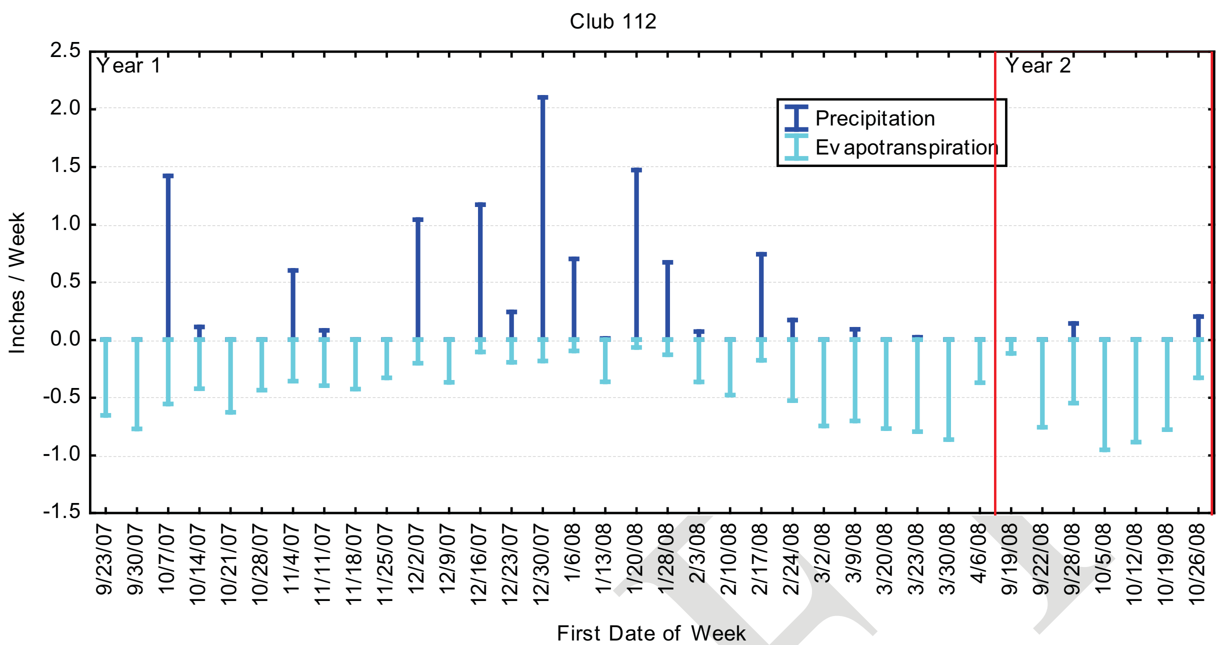


A. Club 112

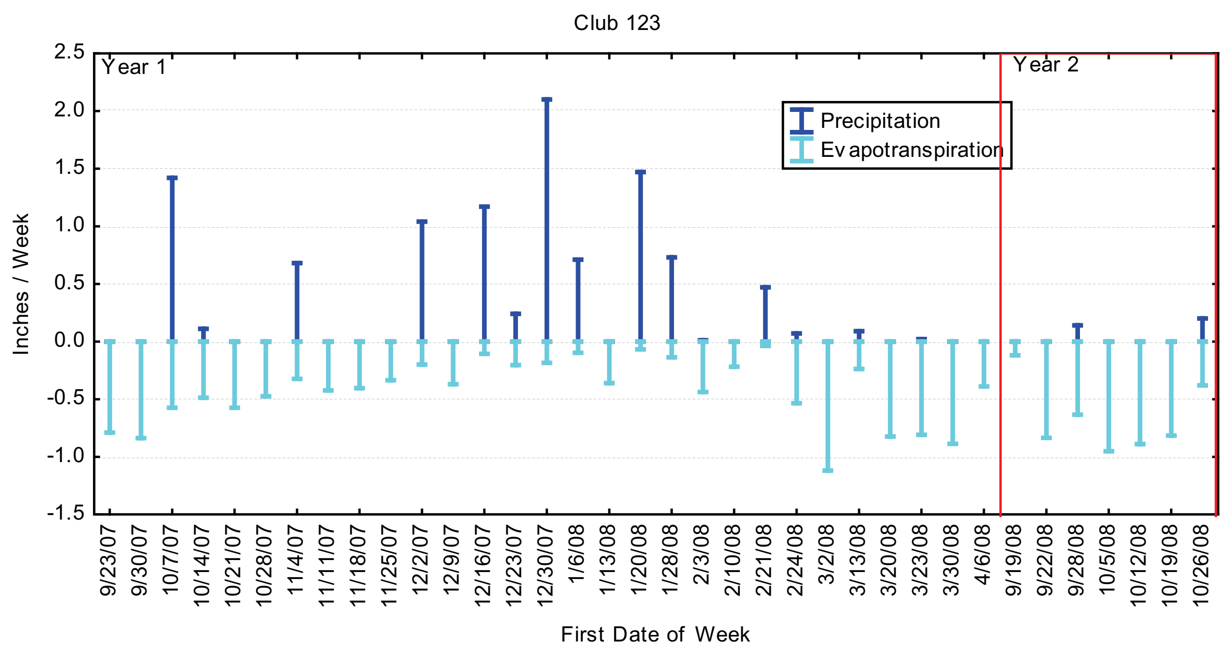


B. Club 123

Figure 15. Applied and discharged water as a percent of current water volumes on the fields
Figure shows the total water applied and discharged from the clubs during the first and second years as a percent of water volume on the club. The weekly value represents the average application or discharge water volume for the week as a percent of the average initial water level for the week. The applied water is as a percent increase over the low water during each club tidal cycle and the high water is a decrease of the high water level during each club tidal cycle. Club tidal cycles are not always synchronous with slough tidal cycles.



A. Club 112



B. Club 123

Figure 16 Weekly precipitation and evapotranspiration totals.

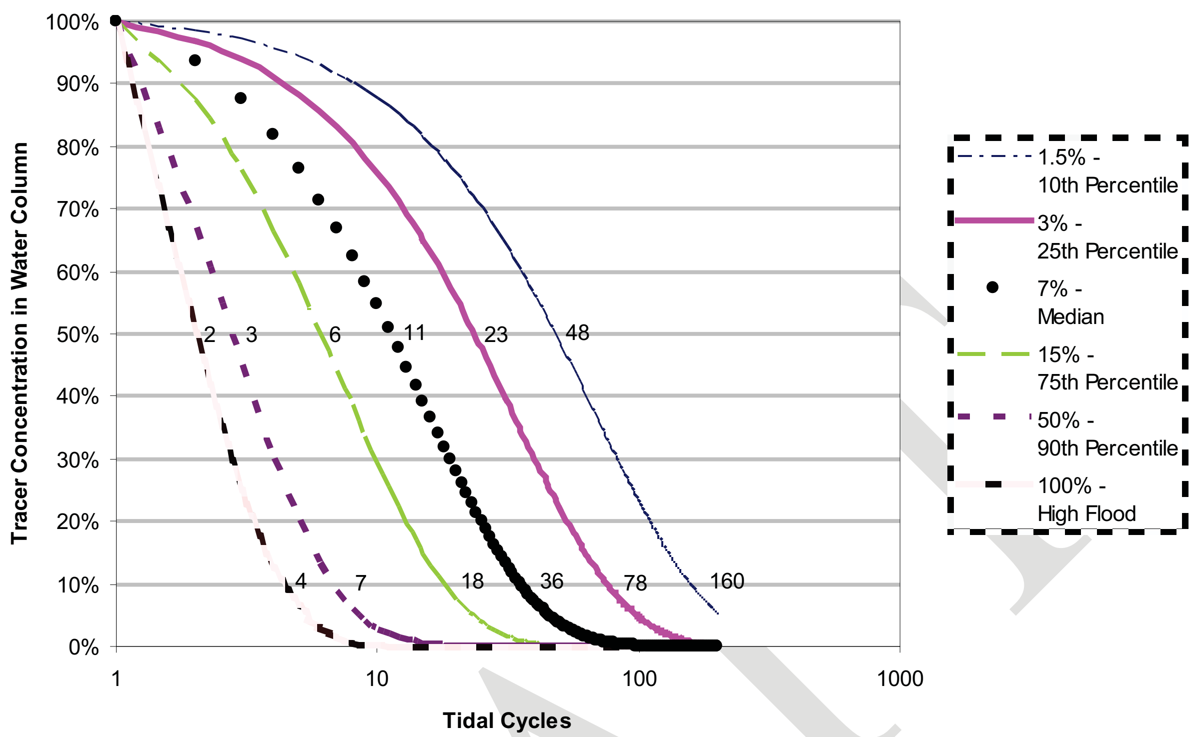


Figure 17. Estimating Mixing

Figure shows the number of tidal cycles needed to reduce tracer concentration to a set amount based upon the amount of water exchanged during each tidal cycle. For instance, under median conditions, 7% of the water column is replaced during each tidal cycle.

Tables

Table 1. Station ID and Characteristics

Station	WCS type [1]	Soil	Vegetation	Elevation (ft NAVD88)	Depth range at shoot level (ft) [2]	Mon [3] Y1	Y2	Landscape Position: At WCS	In Perimeter ditch [4]	In/influenced by marsh channel or swale	In interior Marsh plain	Near sewage effluent point	Management: Mowed	Disked	Chemical Treatment [5]	NA
112-1	24" fbr/flap	An	Open water/ tules	2.3*	3.2 - 3.7	Yes	Yes	X	X						X	
112-2	36" combo/combo	An	Open water/ tules	1.1*	4.4 - 4.9	Yes	Yes	X	X						X	
112-4	none	An	Pickleweed/annual grasses/bare	5.1	0.4 - 0.9	Yes	Yes			X	X	X	X			
112-5	none	An	Pickleweed/annual grasses/bare	4.2	1.3 - 1.8	Yes	Yes			X			X			
123-1	36" fbr/flap	Ta	Open water/ tules	NA	NA	YES	YES	X	X							X
123-2	36" fbr/combo	Ta	Open water/ tules	0.1*	3.9 - 4.4	YES	NO	X	X							X
123-3	36" fbr/combo	Sp	Open water/ tules	-0.6*	4.6 - 5.1	YES	YES	X	X							X
123-4	36" fbr/combo	Sp	Open water/ tules	-0.3*	4.3 - 4.8	YES	YES	X	X							X
123-5	24" combo/combo	Sp	Open water/ tules	-1.5*	5.5 - 6.0	YES	NO	X	X							X
123-6	24" combo/combo	Sp	Open water/ tules	-0.5*	4.5 - 5.0	YES	YES	X	X			X				X
123-8	none	muc	Smartweed/swamp timothy/annual grasses	3.4	0.6 - 1.1	NO	YES			X						X
123-12	none	Sp	Smartweed/masrh aster/watergrass	2.9	1.1 - 1.6	Yes	Yes			X				X		
123-15	none	Sp	Smartweed/swamp timothy/annual grasses	2.1	1.9 - 2.4	Yes	Yes			X	X					X
123-17	none	Sp	Watergrass/smartweed/cocklebur	3.1	0.9 - 1.4	Yes	Yes				X	X	X			
BS	none	NA	Slough	NA	NA	Yes	Yes									
PS	none	NA	Slough	NA	NA	Yes	Yes									

1 Water Control Structure (WCS) types: FBR = flashboard riser, flap = flap, combo = combination screw gate / flap gate. Diameter is inches.
2 112 shoot level = 5.5-6.0 ft NAVD88; 123 shoot level = 4.0-4.5 ft NAVD88
3 Monitoring Year: Y1 = Year 1, Y2 = Year 2.
4 Elevation at perimeter (borrow ditch) stations are taken from bottom of stilling wells. The actual channel bed elevation will be lower.
5 Chemical Treatment ....
6 USDA Soil Type (MUSYM): An = Alviso silty clay loam (silty clay loam), TA = Tamba mucky clay (Mucky clay), Sp = Suisun peaty muck (peaty muck)

Table 2. Club regions.
Clubs were separated in regions based upon similar water level data trends within the region. Data from all stations within a region were averaged and that result was used to characterize hydrologic trends and used in development of water budgets for the region.

Club	Region [1]	Stations	
		Y1	Y2
112	112	112-2, -5	112-2, -5
123	123 N	123-2, -4	123-1, -4
123	123 S	123-5	123-5
123	123 I	123-15	123-15
1	N = North Perimeter, S = South Perimeter, I = Interior		

Table 3. Club Management

Club	Year	Month	Dryland Activities			Water Management Activities						
						Management goal			Management action			
			Mow-ing [1]	Discing	Spraying	Salt leaching	Vegetation Irrigation	Waterfowl use	Flood	Pre-flood [2,3]	Drain	Circulate
123	Pre-Study	Oct-06						x				x
		Nov-06						x				x
		Dec-06						x				x
		Jan-07						x				x
		Feb-07				x		x	x		x	
		Mar-07				x		x	x		x	
	Year 1	Apr-07			125 ac.			x				
		May-07										
		Jun-07										
		Jul-07										
		Aug-07	5 ac.	60 ac.								
		Sep-07						x	x	x	x	
		Oct-07						x				x
		Nov-07						x				x
		Dec-07						x				x
		Jan-08						x				x
		Feb-08				x		x	x		x	
		Mar-08				x		x	x		x	
	Year 2	Apr-08			120 ac.			x				
		May-08										
		Jun-08										
		Jul-08										
		Aug-08	5 ac.	60 ac.								
		Sep-08						x	x	x	x	
		Oct-08						x				x
		Nov-08						x				x
		Dec-08						x				x
		Jan-09						x				x
		Feb-09				x		x	x		x	
		Mar-09				x		x	x		x	
112	Pre-Study	Oct-06						x	x		x	x
		Nov-06						x				x
		Dec-06						x				x
		Jan-07						x				x
		Feb-07				x		x	x(3)		x(3)	
		Mar-07				x		x				
	Year 1	Apr-07			25 ac.			x			x	
		May-07					x	x	x(2)		x (2)	
		Jun-07					x	x	x(2)		x	
		Jul-07					x	x			x	
		Aug-07										
		Sep-07	80 ac.					x		x		
		Oct-07						x	x		x	x
		Nov-07						x				x
		Dec-07						x				x
		Jan-08						x				x
		Feb-08				x		x	x(3)		x(3)	
		Mar-08				x		x				
	Year 2	Apr-08			25 ac.			x			x	
		May-08					x	x	x (2)		x (2)	
		Jun-08					x	x	x (2)		x	
		Jul-08					x	x			x	
		Aug-08										
		Sep-08	80 ac.					x				
		Oct-08						x	x	x	x	x
		Nov-08						x				x
		Dec-08						x				x
		Jan-09						x				x
		Feb-09				x		x	x (3)		x(3)	
		Mar-09				x			x		x	

1 Mowing in 2007 was done with rotary deck mower. Mowing in 2008 was done with flail mo

2 Pre-flood is a preliminary wetting of the marsh plain before full fall flood-up to saturate th
establish flow paths on the marsh plain, and accelerate the decomposition of dead organi

3 The pre-flood at Club 123 in 2008 was followed by a 6 day drying period

Table 4. Recorded Drain and Flood Events

Club		Event	Drain Events								Flood Events						
			Start		End		Calculations				Start		End		Calculations		
			Date	Elev Ft-NAVD	Date	Elev Ft-NAVD	Del Elev Ft	Del Vol Ac-Ft	Duration Days	Qave Ft^3/s	Date	Elev Ft-NAVD	Date	Elev Ft-NAVD	Del Elev Ft	Del Vol Ac-Ft	Duration Days
123																	
	Fall	A									18-Sep-07	2.5	23-Sep-07	4.2	-1.71	-194	4.6
		B	23-Sep-07	4.2	27-Sep-07	2.5	1.76	163	4.4	19	27-Sep-07	2.5	2-Oct-07	4.3	-1.77	-253	5.4
	Winter	A	9-Feb-08	4.1	13-Feb-08	1.4	2.74	239	4.4	27	13-Feb-08	1.4	25-Feb-08	4.3	-2.96	-294	11.6
		B	3-Mar-08	4.4	7-Mar-08	1.4	3.00	305	3.8	41	10-Mar-08	1.4	16-Mar-08	3.8	-2.46	-171	5.3
	Fall	A									22-Sep-08	1.6	28-Sep-08	4.6	-3.06	-360	6.3
		B	28-Sep-08	4.6	3-Oct-08	2.4	2.22	348	5.2	34	5-Oct-08	2.4	14-Oct-08	4.4	-1.98	-288	9.1
	Average						***2.4***	***263.7***	***4.5***	***30.0***					***-2.3***	***-260.0***	***7.0***
112																	
	Fall	A									29-Sep-07	2.6	1-Oct-07	5.3	-2.70	-47	2.6
		B	1-Oct-07	5.3	3-Oct-07	3.7	1.55	42	1.5	15	3-Oct-07	3.7	6-Oct-07	5.2	-1.44	-35	2.2
	Winter	A	30-Jan-08	5.9	2-Feb-08	3.8	2.09	104	3.2	16	2-Feb-08	3.8	6-Feb-08	5.4	-1.66	-55	4.2
		B	6-Feb-08	5.4	9-Feb-08	3.4	2.09	58	2.9	10	9-Feb-08	3.4	14-Feb-08	5.4	-2.05	-55	4.9
		C	14-Feb-08	5.4	19-Feb-08	3.3	2.13	55	5.1	5	19-Feb-08	3.3	25-Feb-08	5.9	-2.64	-113	5.8
	Fall	A1									1-Oct-08	2.7	4-Oct-08	5.2	-2.45	-42	3.2
		A2									14-Oct-08	5.5	19-Oct-08	6.1	-0.57	-71	5.3
		B	19-Oct-08	6.1	22-Oct-08	4.6	1.44	117	2.7	22	27-Oct-08	4.6	3-Nov-08	5.7	-1.11	-66	7.4
	Average						***1.9***	***75.2***	***3.1***	***13.6***					***-1.8***	***-60.5***	***4.5***

Table 5. Weekly Water Budget for Club 112

Site	Year	Season	Date	Average Water Budget By Tidal Cycle (in / tide) [1]							Weekly Totals (in / wk)				Weekly Net On	
				ET	Precip.	On [2]	Off [2]	Net On [2]	Off % Max [3]	On % Min [4]	ET	Precip.	On	Off	in / wk	Ac-Ft/wk
Club 112: 199 Acres	1	Fall	9/10/2007	0.082	0.000	0.061	0.018	0.080	18%	82%	0.6	0.0	0.4	0.1	0.6	9
			9/16/2007	0.043	0.000	0.037	0.007	0.043	7%	45%	0.6	0.0	0.5	0.1	0.6	9
			9/23/2007	0.047	0.000	0.558	-0.337	0.221	-40%	118%	0.7	0.0	7.8	-4.7	3.1	51
			9/30/2007	0.060	0.000	0.446	-0.316	0.130	-17%	29%	0.8	0.0	5.8	-4.1	1.7	28
			10/7/2007	0.040	0.101	0.341	-0.217	0.124	-6%	10%	0.6	1.4	4.8	-3.0	1.7	29
			10/14/2007	0.033	0.008	0.232	-0.163	0.069	-3%	4%	0.4	0.1	3.0	-2.1	0.9	15
			10/21/2007	0.048	0.000	0.326	-0.231	0.095	-4%	6%	0.7	0.0	4.6	-3.2	1.3	22
			10/28/2007	0.031	0.000	0.265	-0.334	-0.069	-6%	5%	0.4	0.0	3.7	-4.7	-1.0	-16
			11/4/2007	0.030	0.050	0.386	-0.164	0.222	-3%	8%	0.4	0.6	4.6	-2.0	2.7	44
			11/11/2007	0.031	0.006	0.216	-0.395	-0.179	-6%	4%	0.4	0.1	2.8	-5.1	-2.3	-39
			11/18/2007	0.029	0.000	0.310	-0.211	0.099	-4%	7%	0.4	0.0	4.7	-3.2	1.5	25
			11/25/2007	0.024	0.000	0.365	-0.291	0.074	-5%	6%	0.3	0.0	5.1	-4.1	1.0	17
			12/2/2007	0.017	0.069	0.237	-0.342	-0.105	-6%	5%	0.3	1.0	3.6	-5.1	-1.6	-26
			12/8/2007	0.022	0.007	0.219	-0.309	-0.090	-6%	5%	0.4	0.1	3.9	-5.6	-1.6	-27
			12/15/2007	0.013	0.073	0.156	-0.237	-0.081	-5%	3%	0.2	1.2	2.7	-4.0	-1.4	-23
			Median	**0.031**	**0.000**	**0.265**	**-0.237**	**0.074**	**-5%**	**6%**						
			Average	**0.037**	**0.021**	**0.277**	**-0.235**	**0.042**			**0.5**	**0.3**	**3.9**	**-3.4**	**0.5**	**8**
			SD	**0.018**	**0.034**	**0.137**	**0.121**	**0.121**			**0.2**	**0.5**	**1.9**	**1.8**	**1.7**	**28**
			Sum								**7.0**	**4.6**	**57.9**	**-50.7**	**7.2**	**119**
		Winter thru Early Spring	12/22/2007	0.015	0.017	0.398	-0.420	-0.022	-7%	7%	0.2	0.2	5.6	-5.9	-0.3	-5
			12/30/2007	0.014	0.162	0.459	-0.561	-0.102	-10%	9%	0.2	2.1	6.0	-7.3	-1.3	-22
			1/6/2008	0.007	0.050	0.269	-0.408	-0.140	-8%	5%	0.1	0.7	3.8	-5.7	-2.0	-32
			1/13/2008	0.029	0.001	0.409	-0.241	0.168	-5%	9%	0.4	0.0	5.7	-3.4	2.4	39
			1/20/2008	0.005	0.105	0.504	-0.489	0.015	-7%	8%	0.1	1.5	7.0	-6.8	0.2	3
			1/28/2008	0.011	0.056	0.158	-0.753	-0.595	-18%	4%	0.1	0.7	1.9	-9.0	-7.1	-118
			2/3/2008	0.026	0.005	0.466	-0.402	0.064	-22%	32%	0.4	0.1	6.5	-5.6	0.9	15
			2/10/2008	0.037	0.000	0.283	-0.332	-0.049	-16%	16%	0.5	0.0	3.7	-4.3	-0.6	-10
			2/17/2008	0.013	0.053	0.552	-0.211	0.341	-9%	24%	0.2	0.7	7.7	-2.9	4.8	79
			2/24/2008	0.038	0.012	0.255	-0.442	-0.186	-9%	6%	0.5	0.2	3.6	-6.2	-2.6	-43
			3/2/2008	0.058	0.000	0.338	-0.094	0.243	-2%	9%	0.8	0.0	4.7	-1.3	3.4	57
			3/9/2008	0.050	0.006	0.310	-0.356	-0.046	-8%	8%	0.7	0.1	4.3	-5.0	-0.6	-11
			3/16/2008	0.064	0.000	0.175	-0.144	0.031	-4%	5%	0.8	0.0	2.3	-1.9	0.4	7
			3/23/2008	0.057	0.001	0.145	-0.126	0.020	-4%	5%	0.8	0.0	2.0	-1.8	0.3	5
			3/29/2008	0.062	0.000	0.260	-0.126	0.135	-5%	10%	0.9	0.0	3.6	-1.8	1.9	31
			4/5/2008	0.064	0.000	0.264	-0.247	0.017	-7%	8%	0.4	0.0	1.6	-1.5	0.1	2
			Median	**0.033**	**0.006**	**0.296**	**-0.344**	**0.016**	**-7%**	**8%**						
			Average	**0.034**	**0.029**	**0.328**	**-0.334**	**-0.007**			**0.4**	**0.4**	**4.4**	**-4.4**	**0.0**	**0**
			SD	**0.022**	**0.046**	**0.125**	**0.181**	**0.208**			**0.3**	**0.6**	**1.9**	**2.4**	**2.7**	**45**
			Sum								**7.1**	**6.3**	**70.1**	**-70.4**	**-0.3**	**-5**
	2	Fall	9/19/2008	0.060	0.000	0.090	-0.020	0.070	-13%	91%	0.1	0.0	0.2	0.0	0.1	2
			9/22/2008	0.063	0.000	0.096	-0.034	0.062	-21%	101%	0.8	0.0	1.2	-0.4	0.7	12
			9/28/2008	0.039	0.010	0.485	-0.206	0.279	-22%	69%	0.6	0.1	6.8	-2.9	3.9	65
			10/5/2008	0.074	0.000	0.226	-0.082	0.145	-3%	9%	1.0	0.0	2.9	-1.1	1.9	31
			10/12/2008	0.064	0.000	0.472	-0.087	0.385	-2%	10%	0.9	0.0	6.6	-1.2	5.4	89
			10/18/2008	0.059	0.000	0.175	-0.530	-0.355	-15%	6%	0.9	0.0	2.6	-8.0	-5.3	-88
			10/26/2008	0.028	0.017	0.407	-0.102	0.305	-4%	16%	0.3	0.2	4.9	-1.2	3.7	61
			Median	**0.060**	**0.000**	**0.226**	**-0.087**	**0.145**	**-13%**	**16%**						
			Average	**0.055**	**0.004**	**0.279**	**-0.151**	**0.127**			**0.6**	**0.0**	**3.6**	**-2.1**	**1.5**	**25**
			SD	**0.016**	**0.007**	**0.173**	**0.177**	**0.245**			**0.3**	**0.1**	**2.6**	**2.7**	**3.5**	**59**
			Sum								**4.5**	**0.3**	**25.2**	**-14.8**	**10.4**	**173**
	Median										**0.4**	**0.0**	**3.9**	**-3.3**	**0.6**	**9**
	Average										**0.5**	**0.3**	**4.0**	**-3.6**	**0.5**	**8**
	10%												**1.5**	**-6.4**	**-2.1**	**-34**
	90%												**6.7**	**-0.9**	**3.5**	**58**

Notes

1 Averaged by tide experienced in Club.

2 "On" = Applied irrigation / flood water. "Off" = Discharged water. "Net" = On - Off.

3 Discharge calculated as % decrease from maximum elevation at beginning of tide cycle

4 Applied as % increase above low tide.

Table 6. Weekly water budget for Club 123

Site	Year	Season		Average Water Budget By Tidal Cycle (in / tide) [1]							Weekly Totals (in / wk)				Weekly Net On	
				ET	Precip.	On [2]	Off [2]	Net On [2]	Off % Max [3]	On % Min [4]	ET	Precip.	On	Off	in / wk	Ac-Ft/wk
Club 123: 335 Acres	1	Fall	9/14/2007	0.058	0.000	0.032	0.025	0.058	42%	57%	0.2	0.0	0.1	0.1	0.2	6
			9/16/2007	0.041	0.000	1.087	-0.306	0.781	-10%	40%	0.5	0.0	14.1	-4.0	10.1	283
			9/23/2007	0.056	0.000	0.978	-1.231	-0.253	-28%	30%	0.8	0.0	13.7	-17.2	-3.5	-99
			9/30/2007	0.064	0.000	1.058	-0.623	0.436	-7%	12%	0.8	0.0	13.8	-8.1	5.7	158
			10/7/2007	0.041	0.101	0.874	-0.958	-0.084	-10%	10%	0.6	1.4	12.2	-13.4	-1.2	-33
			10/14/2007	0.035	0.008	0.628	-0.698	-0.070	-7%	7%	0.5	0.1	8.8	-9.8	-1.0	-27
			10/21/2007	0.044	0.000	0.981	-0.712	0.270	-8%	12%	0.6	0.0	12.8	-9.3	3.5	98
			10/28/2007	0.034	0.000	0.618	-0.757	-0.139	-7%	6%	0.5	0.0	8.7	-10.6	-1.9	-54
			11/3/2007	0.026	0.049	0.624	-0.560	0.065	-6%	7%	0.4	0.7	8.7	-7.8	0.9	25
			11/11/2007	0.030	0.000	0.561	-0.572	-0.011	-6%	6%	0.4	0.0	7.9	-8.0	-0.1	-4
			11/18/2007	0.031	0.000	0.618	-0.581	0.037	-6%	7%	0.4	0.0	8.0	-7.5	0.5	14
			11/25/2007	0.024	0.000	0.576	-0.617	-0.041	-6%	6%	0.3	0.0	8.1	-8.6	-0.6	-16
			12/2/2007	0.015	0.080	0.565	-0.527	0.038	-6%	7%	0.2	1.0	7.3	-6.9	0.5	14
			12/9/2007	0.026	0.000	0.519	-0.589	-0.070	-6%	6%	0.4	0.0	7.3	-8.2	-1.0	-27
			12/16/2007	0.007	0.106	0.619	-0.430	0.189	-4%	7%	0.1	1.4	8.1	-5.6	2.5	69
			Median	**0.034**	**0.000**	**0.619**	**-0.589**	**0.037**	**-6%**	**7%**						
			Average	**0.036**	**0.023**	**0.689**	**-0.609**	**0.080**			**0.4**	**0.3**	**9.3**	**-8.3**	**1.0**	**27**
			SD	**0.016**	**0.040**	**0.271**	**0.279**	**0.257**			**0.2**	**0.5**	**3.6**	**3.9**	**3.4**	**95**
			Sum								**6.7**	**4.6**	**139.5**	**-125.0**	**14.5**	**406**
		Winter thru Early Spring	12/23/2007	0.015	0.017	0.556	-0.635	-0.079	-6%	6%	0.2	0.2	7.8	-8.9	-1.1	-31
			12/30/2007	0.014	0.162	0.772	-0.585	0.187	-6%	9%	0.2	2.1	10.0	-7.6	2.4	68
			1/6/2008	0.007	0.051	0.562	-0.929	-0.367	-8%	5%	0.1	0.7	7.9	-13.0	-5.1	-144
			1/13/2008	0.028	0.000	0.561	-0.544	0.018	-7%	8%	0.4	0.0	7.3	-7.1	0.2	6
			1/20/2008	0.005	0.105	0.794	-0.676	0.118	-7%	8%	0.1	1.5	11.1	-9.5	1.6	46
			1/28/2008	0.011	0.061	0.526	-0.781	-0.255	-8%	6%	0.1	0.7	6.3	-9.4	-3.1	-85
			2/3/2008	0.031	0.001	0.607	-0.981	-0.374	-10%	7%	0.4	0.0	8.5	-13.7	-5.2	-146
			2/10/2008	0.041	0.000	0.501	-1.169	-0.668	-69%	99%	0.2	0.0	2.5	-5.8	-3.3	-93
			2/21/2008	0.006	0.078	0.754	-0.124	0.629	-2%	11%	0.0	0.5	4.5	-0.7	3.8	105
			2/24/2008	0.041	0.005	0.541	-0.353	0.188	-3%	5%	0.5	0.1	7.0	-4.6	2.4	68
			3/2/2008	0.160	0.000	0.551	-1.592	-1.041	-20%	9%	1.1	0.0	3.9	-11.1	-7.3	-203
			3/13/2008	0.079	0.030	1.091	-0.081	1.010	-2%	27%	0.2	0.1	3.3	-0.2	3.0	85
			3/16/2008	0.066	0.000	0.419	-0.164	0.254	-2%	6%	0.9	0.0	5.9	-2.3	3.6	99
			3/23/2008	0.062	0.002	0.418	-0.187	0.231	-2%	5%	0.8	0.0	5.4	-2.4	3.0	84
			3/30/2008	0.063	0.000	0.344	-0.323	0.021	-3%	3%	0.9	0.0	4.8	-4.5	0.3	8
			4/6/2008	0.078	0.000	0.352	-0.409	-0.057	-4%	4%	0.4	0.0	1.8	-2.0	-0.3	-8
			Median	**0.036**	**0.003**	**0.553**	**-0.564**	**0.019**	**-6%**	**7%**						
			Average	**0.044**	**0.032**	**0.584**	**-0.596**	**-0.012**			**0.4**	**0.4**	**6.1**	**-6.4**	**-0.3**	**-9**
			SD	**0.041**	**0.048**	**0.191**	**0.419**	**0.483**			**0.3**	**0.6**	**2.6**	**4.3**	**3.5**	**99**
			Sum								**6.6**	**5.9**	**98.0**	**-103.0**	**-5.0**	**-141**
	2	Fall	9/19/2008	0.060	0.000	0.166	-0.006	0.160	-3%	96%	0.1	0.0	0.3	0.0	0.3	9
			9/22/2008	0.070	0.000	1.329	-0.344	0.986	-5%	21%	0.8	0.0	16.0	-4.1	11.8	330
			9/28/2008	0.045	0.010	0.755	-1.585	-0.830	-39%	30%	0.6	0.1	10.6	-22.2	-11.6	-324
			10/5/2008	0.073	0.000	0.924	-0.233	0.691	-4%	18%	1.0	0.0	12.0	-3.0	9.0	251
			10/12/2008	0.064	0.000	0.573	-0.350	0.223	-3%	6%	0.9	0.0	8.0	-4.9	3.1	87
			10/18/2008	0.059	0.000	0.400	-0.350	0.051	-3%	4%	0.8	0.0	5.6	-4.9	0.7	20
			10/26/2008	0.032	0.017	0.437	-0.376	0.061	-3%	4%	0.4	0.2	5.2	-4.5	0.7	21
			Median	**0.060**	**0.000**	**0.573**	**-0.350**	**0.160**	**-3%**	**18%**						
			Average	**0.057**	**0.004**	**0.655**	**-0.463**	**0.192**			**0.7**	**0.0**	**8.2**	**-6.2**	**2.0**	**56**
			SD	**0.014**	**0.007**	**0.386**	**0.511**	**0.572**			**0.3**	**0.1**	**5.1**	**7.2**	**7.5**	**210**
			Sum								**4.6**	**0.3**	**57.7**	**-43.7**	**14.1**	**393**
	Median										**0.4**	**0.0**	**7.9**	**-7.3**	**0.4**	**11**
	Average										**0.5**	**0.3**	**7.8**	**-7.1**	**0.6**	**17**
	10%												**2.1**	**-13.6**	**-4.3**	**-120**
	90%												**13.7**	**0.0**	**4.7**	**132**

Notes
1 Averaged by tide experienced in Club.
2 "On" = Applied irrigation / flood water. "Off" = Discharged water. "Net" = On - Off.
3 Discharge calculated as % decrease from maximum elevation at beginning of tide cycle
4 Applied as % increase above low tide.

Table 7. Discharges from Fairfield-Suisun Sewer District

	Month	FSSD		Club 112 [1]		
		AC-FT	AC-FT/d	AC-FT	AC-FT/d	% from FSSD [1]
2007 [1]						
	Sep	961	32			
	October	1,296	42	*165*	*5*	*13%*
	Nov	1,327	44	*169*	*6*	*13%*
	Dec	1,530	49	*195*	*6*	*13%*
	Average	***1279***	***42***			
2008						
	Jan	2,089	67	111	4	5%
	Feb	1,818	65	128	5	7%
	March	1,701	55	90	3	5%
	April	1,157	39	0	0	0%
	May	1,160	37	20	1	2%
	June	941	31	0	0	0%
	July			45	1	NA
	Aug	1,092	35	5	0	0%
	Sep	966	32	0	0	0%
	October	1,051	34	120	4	11%
	Nov	1,427	48	235	8	16%
	Dec	1,426	46	147	5	10%
	Average	***1348***	***44***	***75.1***	***2.5***	***5%***

Notes

1. Average flows into Club 112 during 2007 based average of 2008 % diversion from October - December. Estimated values are italicized.

Table 8. Estimated water volumes to saturate soils in the Fall

		Variable		Units	Clubs		Assumptions	Citations
					112	**123**		
Data								
	Water							
		Depth to Water Table	Weighted average	in	36	17	Soil Survey data for September through November	Web Soil Survey 2010
		Pre-flood water content	Weighted average	%	27	41	Calculated average of field capacity (water content 1/3 bar) and wilting point (water content 15 bar)	Web Soil Survey 2010
		Saturated Hydraulic Conductivity	Weighted average	in / hr	0.7	11		Web Soil Survey 2010
			Est Max	in / hr	13	13		Web Soil Survey 2010
			Est Min	in / hr	0.4	1.3		Web Soil Survey 2010
	Soil							
		Organic SG			1.40	1.40		Bogacz and Roszkowicz 2009; Sing et al 2008; Kalantari and Huat 2008; ISRIC 2010
		Inorganic SG			2.65	2.65		Brady and Weil 2002
		% soil organic	Weighted average	%	1.9	43.6	0 - 3 ft	Web Soil Survey 2010
Calculations								
	Pore volumes							
		Total Pore space		%	49	64	Calculated from SG estimates and Bulk Density estimates	Brady and Weil 2002
		Available pore space to saturate		%	21	23		
	Water required to saturate above water table							
			Calculated	in	8	4	Using above data	
				ac-ft	126	110		
			Est Max	in	11	6	50%	
			Est Min	in	4	2	-50%	
	Time to fill							
			Calculated	hrs	11	0	Assume sat and unsat Hydraulic Conductivity differences are negligible in context of calculations	
			Est Max	hrs	30	5		
			Est Min	hrs	0	0		

Table 9. Estimated Water Required to Meet Surface and Soil Water Demand for Suisun Marsh

			Surface Water	
Soil Water	inches		4	8
		ac-ft	17,000	35,000
	2	9,000	26,000	43,000
	12	52,000	69,000	87,000

Appendix C: Water Quality

The Water Quality of Managed Wetlands Studied in the Suisun Low DO and MeHg Project, Suisun Marsh

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Abstract

This water quality study is one component in a compressive assessment of the impacts of wetlands managed as duck clubs (managed wetlands) on the greater Suisun Marsh and their role on depressing DO concentrations. For this study, two managed wetlands (i.e. Wetlands 112 and 123) were studied. Beginning in late September, these two managed wetlands are flooded, drained and reflooded again as a kick-off to duck season. Water levels are then maintained relatively constant under quasi-steady state conditions until around February at which time the wetlands are drained and reflooded two or three times to leach salts from soils. In late spring, the fields are drained again to allow summer agricultural activities in support of waterfowl habitat. All drain events from the two wetlands studied immediately depressed DO concentrations at the wetlands and triggered DO sags in the sloughs. During the fall, DO concentrations in the wetlands were near or at zero mg/L during these drain events and remained so for days at a time with little diurnal variation. DO concentrations in the sloughs also dropped near 0 mg/L remained depressed below the regulatory standard into early December. At this time, DOC, SUVA and meHg were generally elevated on the wetlands with highest concentrations spiking during the initial flood and (first) flush period. Winter DO sags from wetland drain events also occurred but baseline DO concentrations are higher at that time of year and higher flows are occurring in the winter were much higher and thus the DO sags were less consequential. The DO sags likely occur for a number of reasons: exported low DO water from the managed wetlands along the sloughs, the biological oxygen demand of the released DOC, and the amount of dilution from higher DO water. In the fall, reverse flows likely exacerbate DO levels while in the spring high flows likely help to replenish DO. DO may also be causing meHg problems. MeHg concentrations tended to be highest when DO concentrations were under 1mg/L and they dramatically decreased with increasing DO such that at above 4 mg/L DO filtered and unfiltered meHg were below 0.5 ng/L. Both wetlands used different land management practices to control weeds and prepare for hunting season. Wetland 123 relied primarily on discing and Wetland 112 relied primarily on mowing. Wetland 123 typically had higher meHg, DOC and SUVA concentrations. Other factors may explain those differences but the different land management practices may contribute. DOC and u-meHg exports were estimated for the two wetlands. Wetland 123 had greater water circulation rates (~ 3 times higher) than Wetland 112 and generally higher DOC and u-meHg concentrations. Those two factors led to Wetland 123 exporting 4 – 10 times more DOC and u-me Hg than Wetland 112. We calculated export rates from regressions and estimated that Wetland 123 exported an average 826 mg-DOC/m^2 and 31 ng-u-meHg/m^2 per tide event as opposed to 306 mg-DOC/m^2 and 117 ng-u-meHg/m^2 at Wetland 112. Importantly, all that export does not necessarily stay in the sloughs. Tide events push water and their associated loads on and off the wetlands. Thus, some exported loads from an ebb tide return onto the wetlands during a subsequent flood tide. Nonetheless, the effects of these loads can be seen in the sloughs. The typical drainage event from Wetland 112 suppressed DO concentrations in the sloughs by approximately 2 mg/L wherea from Wetland 123 DO sags by about 5 mg/L for Wetland 123.

Introduction

Severely low dissolved oxygen (DO) events resulting from environmental conditions and management actions in some managed wetlands adversely impact the aquatic ecosystem of various sloughs in Suisun Marsh, CA (Schroeter and Moyle 2004). Co-occurring with these events are elevated methyl mercury (meHg) conditions. Peytonia, Boynton, and Suisun Sloughs in the northwest Marsh have exhibited the most significant low DO problems (Schroeter and Moyle 2004). Most the adjacent managed wetlands are dry during the summer and early fall months when land managers carry out maintenance activities with the prime goal of enhancing waterfowl habitat. These systems are then flooded in the fall with water maintained on the marshes into mid-spring. Low DO waters have been documented at the fall flood-up cycle that upon release send low DO plumes into receiving waters (tidal sloughs) impacting aquatic organisms, including killing at-risk fish species and impairing valuable fish nursery habitat (Schroeter and Moyle 2004). Pond releases are also expected to have elevated organic matter with associated biological oxygen demand (BOD), further depressing DO in receiving waters.

Other water quality problems may result from depressing DO concentrations. Methyl mercury (meHg) is produced in low DO organic soils in association with bacterial sulfate reduction (Compeau and Bartha, 1985; Berman and Bartha 1986; Gilmour et al, 1992, Benoit et al 2001).. Wetlands are areas of high meHg production, cycling and export (St. Louis et al, 1994; Hurley et al, 1995; Rudd, 1995) and Heim et al (2007) found meHg concentrations higher in the marsh interiors than their exteriors, and higher in marshes than in open water. The exact amount of meHg and total mercury tMe exports have not been determined for Suisun managed wetlands. High nutrient loading from these wetlands could exacerbate these problems though the data is not certain at this time (Vaithiyanathan et al, 1996; Gilmour et al 1998)

Past research and outreach efforts into the low DO issue have resulted in the development of a variety of management programs for Suisun Marsh (SRCD, 2010) and within these programs are recommended practices:

- Landowners with mosquito production or low DO problems are currently recommended to conduct an early flood-drain cycle prior to bringing ponds to fall management level.
- Once at fall management level, landowners are recommended to circulate water at highest rate possible until temperatures cool (mid-November).
- Landowners are recommended to avoid wetland discharges to dead end drainage sloughs and to redirect discharges to larger sloughs, in order to maximize mixing with tidal waters and thus minimize low DO sags.
- Implementing water management activities to discourage broadleaf plant growth and encourage physical manipulation of this vegetation prior to fall flooding.

This study's purpose is to develop an understanding of the hydrology and water quality within the wetlands and in the surrounding sloughs in order to develop strategies to minimize water quality and hydrologic impacts to the sloughs and their concomitant ecological effects.

This manuscript describes provides an extensive analysis of water quality in managed wetlands and their adjacent sloughs in Suisun Marsh. It assesses DO and salinity responses within the wetlands and in the sloughs in response to hydrologic and vegetation management in the wetlands. It also reviews changes in DOC and methyl mercury concentrations during these periods, developing relationships between these constituents and with DO. Loads exported from the wetlands are estimated, ancillary water quality constituents such as pH, temperature and turbidity are analyzed, and water quality impacts are discussed. Finally, this manuscript discusses the results in terms of wetland management and develops recommendations for improved management in the region.

Site Description

Suisun Marsh lies north of Suisun Bay of the San Francisco Bay Delta system (Figure 1). Two managed wetlands were studied, Suisun Farms (Wetland 112; Figure 2) and Walnut Creek Gun Wetland (Wetland 123; Figure 3). These wetlands are connected to adjacent marsh sloughs via a series of water control structures that allow managers to regulate water levels within the wetlands and exchange with adjacent sloughs.

Methods

Data Collection

Digital Elevation Models

Topographic surveys of Wetlands 112 and 123 were performed in the summer of 2007 by the California Waterfowl Association (CWA). The topographic data were collected using a Real-Time Kinematic (RTK) differential GPS system, and referenced to various established benchmarks in the project vicinity. DEMs with a 3-ft horizontal resolution and elevations in feet, referenced to the North American Vertical Datum of 1988 (NAVD), were constructed from these data using the 3-D Analyst tools in ArcView v3.2. These DEMs were used to develop stage-volume relationships for each of the managed wetlands for use in later analyses.

Hydrologic and Water Quality Data

Hydrologic and water quality monitoring locations are shown in Figure 2 for Wetland 112 and in Figure 3 for Wetland 123. Table 1 describes the characteristics of each station at which monitoring was conducted (e.g.station infrastructure, dominant soil, elevation, landscape position, management setting). These stations were monitored from August to April 2007 and from August to October 2008. Sampling was conducted for water quality, hydrology and soils.

Water quality sampling sites were selected to characterize spatially and temporally water quality in the sloughs, interior to the wetlands and exterior to the wetlands. Wetland 123 had more exterior sites than at Wetland 112 because Wetland 123 receives water from both Boyton and Peytonia Sloughs. Wetland 123 also had more interior sampling sites because it is larger and was expected to have more variance with regard to water quality in the interior because it has multiple water sources. At all these sites, discrete grab samples were collected in accordance with the State of California's Surface Water Ambient Monitoring Program (SWAMP) for constituents with established protocols. Sampling of constituents without SWAMP guidelines conformed to other relevant guidelines (Wagner et. al. 2006; Puckett 2002; USEPA, 1996; USGS National Field Manual for the Collection of Water-Quality Data (http://water.usgs.gov/owq/FieldManual/chapter4/html/ Ch4_contents.html).

Discrete grab samples analyses for dissolved organic carbon utilizing the Shimadzu TOC-5000A Total Organic Carbon Analyzer (Bird et. al. 2003); for Suspended Sediment Concentration (SSC) per SWAMP guidelines using recommended standard method ASTM 2000 D3977 (ASTM 2000); and for filtered and unfiltered methyl mercury (meHg; USEPA 2002).

Continuous in-situ sampling of constituents was conducted utilizing YSI multiparameter probes calibrated to manufacturer specifications. Field activities followed USGS safety guidelines whenever possible (National Field Manual for the Collection of Water Quality Data http://water.usgs. gov/owq/FieldManual/Chap9/chap9.pdf).

More details on water quality and hydrologic sampling and analytical methods are described in the projects Quality Assurance Program Plan (SWRCB 2008)

Pressure transducers and staff gauges were installed at each hydrologic monitoring station. Water levels were recorded at selected internal monitoring locations using externally vented pressure transducers as stand alone probes or as components of a multi-parameter datasonde. At perimeter stations, water levels were recorded with multi-parameter datasondes. Local elevation benchmarks were established at each monitoring station and surveyed into ft-NAVD and used to convert surface water elevations to ft-NAVD. All stations were set to record data on 15 minute intervals and stations were visited monthly during deployment to calibrate and maintain.

Hydrologic data from others included treatment plant data from Fairfield-Suisun Sewer District (FSSD) who measured treatment plant flow to Suisun Marsh and water volumes to each wetland; and Department of Water Resources continuous water level data for Boynton and Peytonia Sloughs.

Climate Data

Meteorology data was collected using the Suisun California Irrigation Management Information System (CIMIS) station (Suisun Valley #123): precipitation, temperature, reference evapotranspiration. Crop evapotranspiration (ET) was estimated using crop coefficients:

$$ET = K_c \; ETo$$

where ET is in in day^{-1}, the K_c value is dimensionless, and ETo is the reference crop evapotranspiration in in day^{-1}.

Data Processing and Calculations

Water quality data was analyzed for spatial and temporal trends using time series analyses, Analysis of Variance (ANOVA), non-parametric analyses, principal components analyses (PCA) and linear regressions (Statsoft, 2008) for individual sites as well as

Data were processed stepwise to develop water budgets and to allow for statistical analyses of the data and those results:

- Developing tidal water volume exchanges;
- Calculating surface water budgets; and
- Estimating subsurface water budgets.

Developing Tidal Surface Water Volume Exchange

Tidal water volume exchanges onto each wetland were developed for each island based upon the results of the monitoring locations. Areas at the two wetland were identified with regard to distint tidal trends (i.e. Wetland 123 northerm perimeter stations, Wetland 123 southern perimeter stations, Wetland 123 interior stations, Wetland 112). For each wetland and their subdivisions, tidal cycles were identified and for each tidal cycle determined the water volume exchange on and off the wetlands, the precipitation and the evapotranspiration. Bachand et al (2010) provides more details on these data which were then used as the basis for determining surface water budgets by wetland for each tidal cycle.

Data Management and Statistical Analyses

A variety of statistical methods including basic descriptive statistics (e.g. means, medians, quartiles, standard deviations), ANOVA (e.g. one-way, two-way, factorial), principle components analyses, and graphical representations (e.g. scatterplots, box plots) were used to investigate trends and assess statistical differences between treatment, with depth and over time (StatSoft 2008). Data was managed with an ACCESS database to allow quick outputs of data under multiple formats and with multiple relationships. The results shown in this study are the key findings from these investigations. These analyses were conducted for individual sites as well as for wetlands by averaging values across subdivisions. Load calculations were conducted as the product of hydrologic load estimates (Bachand et al 2010) and water quality data presented in this manuscript.

Wetland Management

These wetlands were managed using a variety of tools recommended by the California Department of Fish and Game (Rollins 1981) with similar goals as other landowners in the Suisun Marsh: 1) actively managing the wetlands vegetation to achieve a beneficial food source for waterfowl, 2) controlling nuisance invasive vegetation, and 3) reducing potential water quality impacts.

Mechanical techniques primarily include mowing, discing, and herbicidal treatments, which are employed to reduce unwanted or invasive vegetation and reduce vegetative ground cover. Water management involves a series of flood-drain cycles timed throughout the year to reduce soil salinities, and encourage the establishment of a plant community beneficial to waterfowl.

Results

Results in this manuscript focus on providing an understanding of wetland management objectives and practices; spatial and temporal water quality trends, relationships between different constituents, spatial management impact on wetland water quality, short- and long-term temporal trends; estimates of load discharges; and comparison of concentrations at these wetlands to nearby wetlands and slouths. Primarily, these results focus on DOC, SUVA, meHg and DO but also discuss effects to a lesser degree on temperature, SSC, pH and turbidity

Cultural Practices and Wetland Management

As defined in this manuscript, annual operations begin in the spring (April) to prepare for the fall duck season. The management can be divided into both dryland activities and water management activities and these activities vary seasonally (i.e. spring-summer, fall, winter). The key management goals for individual wetlands were to –

- maximize food and cover for waterfowl and wildlife,
- enhance the environment for aquatic invertebrates which are an additional waterfowl food source,
- control salinity
- maximize tidal circulation during the duck season to minimize black water, and
- minimize deleterious effects on the sloughs as discussed in the introduction.

Spring-Summer

Beginning in the spring, fields are drained and herbicides are applied for weed control (e.g. cocklebur, lepidum) beginning in the spring. The initial post-drain spraying occurred at both Wetland 123 and 112 during both years. (Table 2). These activities begin a 1 – 3 month maintenance period where landowners work to maximize food and cover for waterfowl and wildlife, and to enhance the environment for aquatic invertebrates which are an additional waterfowl food source. At both wetlands, mechanical and water management techniques were used during both years to control the vegetation community in the wetland. At Wetland 112, eighty acres were mowed using a standard rotary deck mower in Year 1 and that practice was changed in Year 2 to using as flail mower to more completely chop and shred cut biomass. At Wetland 123, mechanical activities including discing 60 acres and mowing 5 acres during both years. As with Wetland 112, the rotary deck mower used during Year 1 was replaced with a flail mower.

By the early spring and a couple months past the close of duck hunting season, the fields at both wetlands had been drained. During May and June during both years, water managers at Wetland 112, performed approximately flood-drain irrigations each month from April 15 to July 15. After those irrigations, the wetland was drained for the remainder of the summer. A Wetland 123, the fields were drained after April 15 for both years and remained drained throughout the summer.

Fall

During the first year, Wetland 112 was flooded from September 28 to October 2, drained from October 2 to October 4, and then reflooded. Once flooded to desired height the water was circulated at the highest rate possible allowable through tidal exchange. During the second year, flooding occurred from October 1 through October 5 and then water levels were maintained thereafter. Wetland 123 was managed similarly to Wetland 112 during the first year with an initial flooding from September 17 through September 23, draining from September 23 through September 28 and reflooding after September 28, with maximized circulation attempted thereafter. Water was managed similarly again in Year 2 with an initial flooding from September 21 through September 28, draining from September 28 through October 4, and then reflooding thereafter.

Winter

For Wetlands 112 and 123, water managers sought to maximize circulation rates. At the end of the winter, the wetlands were drained.

During Year 1, water managers drained the marsh plain at Wetland 112 and then performed a series of two flood-drain cycles to leach salts from the soils. After the last leach, the water level was held at half of the normal (shoot level) height until April 15, when the entire wetland was drained. This practice was repeated in Year 2. At Wetland 123, the water managers drained the marsh plain of the wetland and then performed a series of two flood-drain cycles to leach salts from the soils. These cycles occurred during February and March. After the last leach, the water level held at half of the normal (shoot level) height until April 15, when the entire wetland was drained for the remainder of the summer. This practice was again repeated in Year 2.

Dissolved Oxygen Water Quality Trends

Figure 4 shows temporal DO concentration changes at the perimeter stations for Wetlands 112 and 123 using 15 minute data and Figure 5 shows corresponding percent saturation data. Both show least square fit trend lines (Statsoft, 2008).

Data collection during 2007 and 2008 began in late September. At Wetland 123, DO levels drop to near 0 mg/L around September 24 (Figure 4). This decrease occurs at all the stations but at Stations 123-1, 4, 5 and 6 DO flat lines near 0 mg/L for three to four days. This trend occurs again in 2008 when around September 29 DO flat lines again at Stations 123-1, -3, and -4 for three to five days. At Wetland 112, the drop in DO is more drastic. In 2007 beginning around September 11, DO flat-lines near 0 mg/L for about five to fifteen days, depending upon location. In 2008 the trends are slightly different at Wetland 112 with two dips in DO, one beginning around October 9 and one beginning around October 22. Each dip last for about two to six days. Thus, in 2008, DO is near 0 mg/L in the fall for about seven days at the two monitoring locations.

These changes in fall DO levels are in response to discharges from the wetlands as indicated by water level drops (Figure 6). Water was drained at Wetland 123 beginning on September 24, 2007 and on September 29, 2008 and at Wetland 112 beginning on October 2 and in 2008 beginning on October 20 (Figure 6). At Wetland 112, a subsequent but small drain event beginning on November 4 did not affect DO much.

At both wetlands, drain events also occurred in the late winter. Wetland 112 drained three times beginning on Jan 30, February 6 and February 15. Wetland 123 drained twice during that same period beginning on February 9 and March 3. During these winter drain periods at both wetlands, DO levels dropped in response to the drain events but less than during the fall.

Figure 7 focuses on DO response at Wetland 123 during the three drainage periods discussed above. Immediately upon draining water from the Wetland, DO levels drop dramatically to near 0 mg/L. The response in the fall is very extreme with DO essentially flat-lining at 0 mg/L. In the spring, DO drops to 0 mg/L but diel variations allow for DO levels to rise to over 5 mg/L. Once the fall drain events are over, DO levels tend to recover. The initial recovery is rapid though not complete with DO levels averaging around 3 – 5 mg/L (Figure 7) and then slowly increasing over the next two months until around December when the exceed the water quality objective for DO of 7 mg/L (Figure 4).

At Wetland 112 the DO trends are slightly different. DO concentrations begin decreasing in the fall upon the initial flooding period (Figure 8). During both fall periods, DO concentrations are near 0 mg/L during periods of drainage, even when relatively minor. DO levels are repressed much longer then at Wetland 123 and at some stations DO levels are below the water quality standard into December (Figure 4). During the spring, DO levels at Wetland 112 fall with the drain events though they are never as low as at Wetland 123. The DO recovery in the spring is relatively slight during the reflooding until water levels are pretty high.

During the second year, continuous water quality data was monitored in the marsh at Stations 123-7 and -8. Both are similar and Station 123-8 is shown. DO levels are near 0 mg/L at the internal stations through the entire period DO was monitored during the second year.

Drain events from the wetlands directly affect the water quality in the sloughs. Figure 9 shows the DO concentrations in Peytonia and Boynton Sloughs in response to drain events. The figure identifies with black gridlines the beginning of drain events from the wetlands. The label on the top axis identifies which wetland the drain event occurs. The lower X-axis identifies dates including the beginning date of the different flood events. The water quality standard for DO concentration (7 mg/L) is shown in the figure and dates identify when the sloughs are above and below the standard.

During the first year, DO concentrations are below the water quality standard from around September 20 through December 11. DO concentrations are then generally above the water quality standard until April 10, 2008 and then below the standard until August and September when DO diel variations lead to DO concentrations moving above and below the standard. DO concentrations then fall below the standard beginning around October 21, 2009 and remain so into early December.

Fall drain events from both wetlands appeared to affect DO concentrations in the sloughs. After the fall drain events from Wetland 123, DO levels in the sloughs drop steeply and oftentimes down below 0 and 2 mg/L during the drain event. Peytonia Slough in the north is generally more greatly affected. Fall drain events from Wetland 112 also coincided with dropping DO levels in the sloughs and those effects were greater in the second year of the study. Generally, DO drops of about 5 mg/L occurred when water was drained from Wetland 123 as compared to drops of about 2 mg/L when water was drained from Wetland 112 (Figure 9).

Winter drain events affect slough DO concentrations less. After each winter drain event, DO levels in the sloughs decreased. Wetland 123 winter drain event appeared to have the greatest effect on slough DO concentrations. Wetland 112 affected slough DO concentrations three times during this same period because of multiple drain events. During this winter period, DO concentrations in the sloughs normally ranged between 6 and 10 mg/L, with diel variations. During drain events, DO normally stayed near or above the water quality standard though after winter drain events DO concentrations could drop as low as 2 – 4 mg/L.

Other continuous water quality data: salinity, EC, pH, Temperature and TSS

Other water quality parameters varied temporally in the wetlands.

Salinity showed both short- and long-term temporal trends with some spatial variation as well. First, Wetland 123 showed diurnal variations in salinity with those variations greatest on the eastern edge of the wetland (Figure 10). At Wetland 123, salinity levels varied diurnally 2 – 6 ppt (depending upon location) during both falls. Station 123-3 and -4 had the greatest diurnal variations for their respective sloughs. These stations were located on the eastern side of the wetland and likely received the greatest exchange. The remaining wetlands had more similar diurnal varations. This diurnal variation was not exhibited at Wetland 112. Second, both wetlands showed a long term decrease in wetland salinity during the falls. At Wetland 123, salinity dropped from about over 7 ppt (nearly 10 in the second year) to 1 – 2 ppt in the winter and then generally remained at those low levels. At Wetland 112 salinity showed similar trends though slighty less extreme.

Other water quality changes also occurred though these were generally less varied spatially. Water temperatures also changed temporally though these changes were similar at the perimeter stations within and between the wetlands. Water temperatures were near 20 degrees C during early fall and decreased to about 8 degrees C in the winter (Figure 11). pH was generally in the 6.5 to 7.5 range during the fall throughout Wetland 123 though increased to an average of around 9 after the two successive winter drain events. Wetland 112 had higher pH levels in the fall, in the range of 7 to 8.5, and the also experienced an increase in pH during the winter drain period (Figure 12). TSS was generally low throughout the periods though spiked occasionally. These spikes may have been in response to drain and flood events and their disturbance to sediments. Chlorophyll also was generally low though like TSS had some elevated levels (Figure 14). Chlorophyll data at Wetland 123 suggests algae growth occurred from September through early November, and then ceased until January and February, at which point it rebounded. Wetland 112 shows more algae blooms and for longer periods of activity.

Discrete Water Quality Data Temporal and Spatial Overview

Table 3 summarizes the discrete water quality data collected from these wetlands during the study period. During this study, approximately 300 samples were collected from the various sampling sites for DOC and SUVA, about 225 samples for Hg, and about 80 samples collected for specific conductance (SC), suspended sediment concentration (SSC), pH, temperature, turbidity and dissolved oxygen (DO). In the discrete sample pool, constituents generally varied by one to two orders of magnitude. DOC ranged from under one to over 100 mg/L, meHg (filtered and unfiltered) ranged from approximately 0 – 15 ng/L. Turbidity ranged from under 3 to over 80 NTU. Even pH and temperature saw great variation over the season. pH was as low as 5.7 and as high as 8.8. Temperature ranged from a low of 12 to a high of 27 deg C. Median values were generally in the range of 70 – 90% of the mean values indicating a constituent distribution more skewed towards the low end then found with a normal distribution. SUVA, f-meHg and u-meHg were the most skewed with median values respectively 10, 40 and 60% of the corresponding mean. To better understand the data, these data were analyzed for both temporal and spatial trends and relationships.

Temporal Trends and Relationships

Temporal trends are shown in Figure 15 through
Figure 18 for DOC, SUVA and filtered and unfiltered methyl mercury. The top axis shows with the corresponding black gridline shows when a fall drain event initiated and at which wetland.

These water quality constituents were the most often sampled and key constituents being studied here (Table 3). These temporal trends cover first year results from September 2007 through March 2008 and second year results from September 2008 through November 2008. Data presented in these graphs are categorized by the wetland location and whether the data was from interior or perimeter sampling locations as described in Table 1. Importantly, water sample scheduling during the second year was over a shorter period then during the first year but focused more heavily on flood and drain events, implementing a higher density of sampling during those periods.

Wetland 112 shows DOC concentrations averaging around 20 – 25 mg/L during the first fall at both the interior and perimeter sites (Figure 15). These measurements are about 7 – 10 days after the initiation of a drain event. DOC concentrations begin to decrease in early November and by December are averaging about 10 mg/L, staying flat through the winter. The following fall shows similar trends though DOC concentrations are averaging about 50% higher initially at about 30 mg/L with some stations higher. These concentrations during the second fall occur from early flooding and for several weeks after the first drain event. By initiation of the second drain event, DOC concentrations are somewhat lower and then are stable into early November at about 10 mg/L again at the perimeter stations and 20 mg/L at the interior stations.

Other water quality constituents measured at Wetland 112 are not easily predicted from the DOC trends. SUVA is near zero throughout the entire sampling period except for the flood drain events in September and October 2008 (Figure 16). Filtered meHg concentration trends somewhat follow DOC trends for Wetland 112. During the first year at the interior and perimeter stations, concentrations peak at about 1.5 ng/L in the fall period coinciding with the peak in DOC. Filtered meHg concentrations then decrease to near 0 ng/L for the remaining first year sampling period (Figure 17). During the second fall period, filtered meHg concentrations again peaks between 1 – 1.5 ng/L though the peak is much shorter lived then during the first year. Unfiltered meHg concentrations also show peaks in the fall period for both years. Concentrations at the stations vary greatly during the fall period ranging from near 0 to over 7 ng/L (
Figure 18). This result is in comparison to winter results in which unfiltered meHg is never over 2 ng/L.

Wetland 123 shows fairly similar results to Wetland 112, though the magnitude of concentrations is generally higher. DOC concentrations are high in the fall periods in comparison to the winter (Figure 15). Average concentrations in the fall are as high as 40 mg/L for the perimeter stations during Year 1 and 40 – 60 mg/L for all stations during Year 2. At individual locations DOC reached as high as 140 mg/L during the fall flood event. In comparison, average winter concentrations are again about 10 mg/L. Highest values coincide with the drain events.

SUVA is flat in Year 1 for Wetland 123 as was at Wetland 112 (Figure 16). The Year 1 data begins after the end of the fall drain-flood cycles when maintenance flows are being maintained. In Year 2, mean SUVA values are as high as about 220 L/mg-m at the perimeter stations and 250 at the interior stations. These occur at the drain event. As with Wetland 112, f-meHg at Wetland 123 trends similarly to DOC (Figure 17). However, peaks at Wetland 123 are much higher than at Wetland 112. During the fall periods for both years, filtered meHg is commonly in the range

of 2 – 8 ng/L as compared to winter values which are always less then 2 ng/L. Unfiltered meHg concentration trends are also similar between the wetlands though concentrations are generally higher at Wetland 123 (
Figure 18). Ranges for unfiltered meHg are only slightly higher then for filtered meHg, indicating that most of the meHg is in dissolved form.

Figure 20 presents median and quartile concentrations of DOC, SUVA and methyl mercury species at Wetlands 112 and 123 during the three different water management conditions (i.e. flood, drain, maintenance flow). These regimes occurred at the wetlands during the early fall and the mid winter.

Analyte concentrations are very similar between the different water management conditions and between the two wetlands with some exceptions. At Wetland 123, DOC, SUVA and u-meHg median levels and their range (as defined by the quartiles) are higher during the drain events than for any of the other conditions graphed in Figure 20. In general, u-meHg concentrations are higher at Wetland 112 then at Wetland 123 though drain events at Wetland 123 have the highest u-meHg concentrations. F-meHg is generally lower at Wetland 112 than at Wetland 123.

Spatial Trends and Relationships

Spatial trends and relationships were considered for the entire period of the study on a station-by-station basis as well as by categorizing island areas for specific temporal periods.

Figure 21 shows median DOC, SUVA and meHg concentrations across the different stations at Wetland 123. This figure presents all the data for these stations and thus represents the entire period for this study. As discussed earlier (Table 1, Figure 3), Stations 123-1, -2, and -3 represent perimeter stations discharging to the north into Peytonia Slough and Stations 123-4, -5, and -6 represent perimeter stations discharging to the south into Boynton Slough. Station 123-7 is at the outfall box for the wastewater discharge from Solano WWTP. According to SRCD the discharge from that location also affects Stations 123- 6, -16 and -17 (Table 1). Stations 123-8 through -20 are interior stations to the marsh.

In general, all the perimeter stations have lower concentrations of DOC and meHg than at the interior stations. The lowest concentrations of these three constituents are found at Station 123-7. SUVA concentration median values are more uniform throughout the wetland though the variance is much less at the perimeter stations than at the interior stations. At Wetland 123, effluent discharge at Station 123-7 changes the water quality signature at that location but does not seem to affect water quality at other stations near the outfall (i.e. Stations 123-6, -16, -17) suggesting water quality effects from the treatment plant effluent are very localized for Wetland 123.

Figure 22 presents a similar dataset for Wetland 112. Stations 112-1 and -2 are perimeter stations and Station 112-3 is an effluent discharge locations. According to SRCD, Station 112-4 is also affected by the effluent due to its nearby proximity to Station 112-3.

For Wetland 112, the DOC and meHg trends are different. Stations 112-1 and 112-2 are the perimeter stations at Wetland 112. Both stations discharge into a small slough but Wetland 112 is not directly adjacent to a major slough as is the case with Wetland 123. Thus, the interior and perimeter stations have similar median concentrations for DOC, meHg and SUVA and those constituents have similar variance range. The only station with very different concentrations is Station 112-3, the effluent outfall box of Solano WWTP. As with Wetland 123, effluent effects appear very localized as Station 112-4, the station relatively near to Stations 112-3, has very different concentrations of DOC, SUVA and meHg then Station 112-3.

ANOVA Analyses considering Spatial and Temporal Trends

From the above temporal and spatial analyses, several factors were considered further using ANOVA analyses. We first considered sampling locations, wetland and water management regime. Sampling locations referred to whether a station was an interior or perimeter station (identified by the treatment factor ExtInt). Water management regimes included whether the system was being flooded, drained or maintained under continuous flow conditions. We analyzed changes in DOC, SUVA, and filtered and unfiltered methyl mercury as they were considered key constituents and were the most frequently sampled (Table 1).

Using a factorial 3-way ANOVA for these three factors, DOC, SUVA and f-meHg concentrations differed significantly ($p<0.05$) between the different water management regimes and the two wetlands. DOC concentrations differed significantly between the interior and perimeter sites (Table 4). Figure 23 shows the mean values and the 95% confidence intervals for these ANOVA results for these constituents at the interior and perimeter sites for different water management regimes. The significant differences shown in the ANOVA results are primarily due to differences at Wetland 123 and not Wetland 112. At Wetland 123, drain events consistently have the highest concentrations for all constituents. This difference is greatest at the perimeter locations where drain events are about 3X higher for DOC, 3 – 7X higher for unfiltered meHg and 3 – 20X higher for filtered meHg. SUVA is 50X higher. Interestingly, mean concentrations of all constituents tend to nonetheless increase from the perimeter to the internal locations. During the continuous and flooded water management regimes, mean concentrations of DOC and meHg at the internal stations are 15 – 3X higher for DOC, 2 – 4X higher for unfiltered meHg and 2 – 9X higher for filtered meHg.

Other ANOVA analyses were conducted. ANOVA analyses were conducted to assess spatial differences in water quality between interior sites based upon management (Table 1). Only a few of those spatial characteristics are managed and only those characteristics were considered. Thus, the spatial conditions considered were whether the location had been subjected to land preparation practices such as mowing or disking and whether the location was at a wastewater effluent discharge location. DOC, SUVA and meHg did not differ statistically for the different management practices (not shown). Effluent effects were also considered in a 3-way ANOVA of water management v wetland v outfall. DOC and u-meHg differed statistically at outfall sites as compared to non-outfall sites and the other constituents were marginally not statistically significant ($p<0.10$).

Relationships between Water Quality Constituents

Relationships between the water quality constituents were developed. Table 5 presents the relationships between key constituents with DOC, DO and unfiltered meHg. These relationships are shown between the internal stations, the perimeter stations and all stations together (pairwise deletion). Most the relationships are statistically significant ($p<0.05$) but in general the correlations explain less then 50% of the variance. For the internal stations, DOC shows a strong and significant relationship with both SUVA and UV-254. For the perimeter stations, DOC shows a strong and significant relationship with meHg, SUVA and UV-254. For the perimeter stations, nearly all constituents show a strong and significant relationship with DO, DOC and unfiltered meHg.

Figure 24 graphically presents the relationship at the interior and perimeter sites between DO and filtered and unfiltered meHg. At the perimeter sites, both filtered and unfiltered meHg drop precipitously from the high values at 0 to 1 mg/L as DO increases. At those low DO levels, filtered meHg is often as high as 4 ng/L and unfiltered is often between 4 and 8 ng/L. However, for DO levels above 1 mg/L, filtered meHg is usually below 0.2 ng/L and unfiltered is usually below about 1 ng/L. At the interior sites, the trends with DO are much different. Filtered meHg ranges from about 0 – 4 ng/L and the trend is relatively flat for DO levels from 0 – 8 mg/L. Unfiltered meHg is generally flat for the same DO range with mean levels around 2 ng/L.

Estimates of Load Discharges

Loads were calculated for DOC and methyl mercury at the perimeter stations. Tidal flows for the wetlands were estimated in Bachand et al (2010). Concentrations used for calculating loads were average concentrations at the perimeter stations for each sample event. These concentrations were used for calculating loads on and off the wetlands because 1) no water quality data was available from the adjacent sloughs and 2) there was no statistical difference found in these water quality constituents between ebb and flood conditions ($p<0.05$).

Table 8 presents the results of the regression of load versus flow with both variables standardized against wetland area:

$$Load = m \times Flow$$

where "m" = the slope of the curve. Essentially, "m" represents an average concentration value multiplied by a conversion constant. For imported loads, a single regression is used because both wetlands were fed by the same sloughs. However for exported loads two regressions were done, one for each wetland. These calculations for the regression including p-values, correlation coefficients and lower and upper confidence limits.

When considering imported water quality constituents, only the relationship for DOC is statistically significant, accounting for about 50% of the variance in the data. For exported constituents, or exported loads, a greater amount of the variance is accounted for. 94% of the variance is accounted for with the calculated regression for DOC, 65% for unfiltered meHg and 77% for filtered meHg. All the exported calculations are statistically significant for Wetland 123. Only filtered meHg is far from being statistically significant for Wetland 112. We expected the regression for imported loads to account for less of the variance then the regression for exported loads. This expectation was based upon the methodology using wetland concentrations for calculating the imported loads and consolidating the wetlands rather than using concentrations from the adjoining sloughs. Though ebb and flood concentrations were not significantly different as stated earlier ($p<0.05$), the wetland concentration is nonetheless a loose proxy for the concentrations in the adjacent sloughs.

Based upon the analyses, each inch of water during a flood event loads 470 mg per square meter of wetland. Typically, up to about 2 inches of water is imported per tidal event. We calculate the amount of DOC exported to be 306 and 826 mg/m2/in/tide for Wetland 112 and 123 respectively (Table 8). During flood and continuous water management regimes, 0 – 1.5 inches were typically discharged. During drainage events, the outflow increased up to over 4 inches per tide event.

Predictions for load estimates of methyl mercury are less certain than for DOC (Table 8). The estimates for imported mercury are very poor as they explain very little of the variance in the data. The calculated exports are better, explaining 65% of the variance for filtered meHg and 77% for unfiltered meHg. Wetland 112 estimates are not as strong based upon the p-value. However, unfiltered meHg calculations for both wetlands are reasonable with a p-value of 0.10 for Wetland 112 and $\ll 0.01$ for Wetland 123. That regression estimates that Wetland 112 exported approximately 31 ng/m2/inch of outflow/tide whereas Wetland 123 exported three times higher at 117 ng/m2/inch of outflow/tide.

To fully appreciate loads being discharged it is important to understand the volume of water being discharged per tide event under the different water management regimes and between wetlands. Figure 25 provides the average, minimum and maximum amount of water discharged per area from each wetland for the different water management objectives. These results are presented seasonally. This figure shows that water volumes on and off are typically 2 – 3X greater for Wetland 123 then for Wetland 112. This result is generally true for all seasons and all water management objectives (i.e. flooding, draining, continuous maintenance flows). During flooding periods, more water is applied to all the wetlands as measured as a tidal average or the maximum during that management period when compared to the other water management periods. This is true at both wetlands during both seasons. Typically, drain periods generally have greater average discharges. Wetland 112 shows less differences but Wetland 123 shows very distinct differences. For Wetland 123, average discharges during managing the wetland for draining are about 2X higher than when managing under continuous maintenance conditions.

Table 9 provides an estimate of average load being exported during tide event during the different water management periods during each season integrating the data presented in Figure 25 and Table 8. These values are standardized to the area of the wetland on a per meter square basis and are presented on a seasonal basis. This table estimates that DOC load discharges from Wetland 123 are much greater then at Wetland 112 due to both the larger load export on a per inch of discharge water basis as well as because of the larger amount of water discharged per tidal event. These estimated loads are discharged into the slough on each tide. Some of the discharged water is pumped back onto the wetlands during the flood period of each tidal cycle. During periods of continuous maintenance flows, these loads may be somewhat similar as similar amounts of water flow on and off the wetland during that period. During periods in which wetlands are being flooded, the wetlands may be sinks for the loads as more water flows onto the wetland than off, especially for Wetland 123. However, during periods of drain flows, loads being discharged are going to be much higher than those being imported back onto the wetlands due to the net volume of water being exported.

Comparisons with Surrounding Areas

The final results we consider are considering the water quality characteristics of the sloughs and other wetlands. Relatively equivalent data sets were developed for a set of nearby wetlands and Montezuma Slough from October 2007 through January 2008. Figure 26 shows these data. DOC at the wetlands was generally in the same range for all the wetlands and much higher than found in Montezuma Slough. In general, median monthly DOC generally ranged from about 13 – 22 mg/L at the five wetlands from October through December and decreased to a range of 7 – 18 mg/L in January. In Montezuma Slough , median monthly DOC was in the range of 3 to 8 mg/L during the entire time period. SUVA was relatively the same from month to month and from wetland to wetland, generally in the range of 3 – 4 L/mg-m. Only Wetland 112 showed very high SUVA values in October, at nearly twice that value. The slough SUVA concentrations were nearly identical to values for the wetlands during the entire period. Finally, meHg data were less complete. Variance was oftentimes relatively high compared to DOC and median ranges for f-meHg ranged from near 0 – 0.8 ng/L and for u-meHg from near 0 – 3.5 ng/L. Wetlands 112, 123 and 530 had generally higher concentrations of filtered meHg than Wetlands 525 and 529. For unfiltered meHg, Wetland 525 had much lower concentrations than the other wetlands. When measured, filtered and unfiltered meHg concentrations were low with concentrations of both filtered and unfiltered meHg typically less than 0.15 ng/L.

Results Summary

Results are summarized below with regard to key findings:

- Both studied wetlands (112, 123) used very different management approaches to prepare for duck season. Beginning in April both years, Wetland 123 applied herbicides to about 40% of their acreage and Wetland 112 applied to about 12% of their acreage. During August and September, discing occurred on nearly 20% of the total 335 acres on Wetland 123 as compared to no discing on Wetland 112. Also during this period, mowing occurred on only about 1.5% of the acreage on Wetland 123 but on about 40% of the acreage on Wetland 112.
- Both wetlands managed their water fairly similar during both years of this study. In general, both wetlands were flooded, drained and then reflooded in early fall. Once the wetland was reflooded, water was kept at desired height and tidal exchange was used to circulate water. During the second year, a change was made to allow a greater drying period between flooding at Wetland 112. In the winter, the management was less similar. Wetland 112 experienced three drain-flood cycles in early winter with the goal of draining the salts. These cycles occurred relatively rapidly during February. Wetland 123 experienced two drain-flood cycles and these occurred during February and March. Both fields were drained in April.
- Dissolved oxygen concentrations in waters being exported from the wetlands drop near or to 0 mg/L during the fall drain events during which water elevations are dropped in the wetlands to at or below marsh level. These drain events were implemented to manage organic carbon discharges to the sloughs. However, these drain events lead to the worse DO conditions in export water. DO concentrations are continuously near or at 0 mg/L at

several discharge locations for about 3 – 5 days at Wetland 123 and for about 5 – 15 days at Wetland 112. These conditions are continuous and diurnal. After the drain events, DO remains depressed into November and December. DO concentrations drop to or near 0 mg/L but these drops are short-lived and part of a diurnal cycle which typically sees DO vary by about 3 – 5 mg/L during tidal events.

- Fall drain events from Wetlands 112 and 123 affected DO levels in the adjacent sloughs. Each fall drain event triggered declines in slough DO concentrations with slough DO levels dropping occasionally to 0 mg/L. Slough DO concentrations were depressed below their initial conditions in early spring from the beginning of the fall draining into December. Spring drainage events also trigger decreases though these decreases have much shorter impact on the slough DO concentrations.
- Baseline DOC concentrations for the perimeter and interior sites is in the range of 10 mg/L and for our data set these concentrations were experienced through the winter. At both Wetland 112 and 123, general responses to water management can be extrapolated from reviewing data for both sample years. Based upon both years it appears DOC concentrations begin to rise during the early flooding period which occurs in mid to late September. The rise in concentration can be very high and concentrations continue to be elevated for about 3 – 6 weeks, depending upon the location and the wetland management. At Wetland 123, DOC concentrations are clearly highest during the drain events with both the highest median values and the greatest range of values. At Wetland 112, there is no clear difference in DOC concentrations for the different water management regimes. These concentrations trends are fairly similar between the perimeter and interior sites at the wetlands.
- SUVA data tells us about the DOC quality. SUVA concentrations spike with the initial fall flooding are highest during the fall drain events. Those spikes vary by an order of magnitude for the two wetlands. After about one month of flooding, SUVA concentrations drop near zero and remain so for the remainder of the year.
- Methyl mercury trends tend to track those for DOC though the variance in the data is much greater. Methyl mercury tended to be highest during the drain events with higher median values and a greater range of the data.
- Water quality spatial distribution differs between the wetlands and this appears to be due to their overall hydrology. At Wetland 123, water quality at the perimeter stations differed from that at the interior with DOC and meHg concentrations lower than at the interior sites. Wetland 123 receives water directly from Boynton and Peytonia Sloughs. At Wetland 112, water quality is more similar amongst all sites. Wetland 112 receives water less directly along sub-sloughs and small channels. For both wetlands, the lowest DOC concentrations, methyl mercury and SUVA values and the highest DO levels were at stations receiving effluent discharges.
- Land management effects on water quality appear relatively short-lived. Land preparation work at the Wetlands included mowing, discing and applying herbicides. Both wetlands had different water quality responses to land preparation. For Wetland 112, stations in which land preparation occurred had higher DOC and SUVA levels during periods in which the wetland was being managed to drain waters. For Wetland 123, those constituents increased during the time the wetland was being managed to flood the wetland.

- Export water dissolved oxygen concentrations during the spring are depressed below the levels that occurred during flow maintenance conditions. DO concentrations dropped to near or at 0 mg/L during these spring drain events. However, periods of extended DO near 0 mg/L were much shorter when compared to the fall. Diurnal cycles tend to pull DO concentrations up during this period with DO levels typically varying by 5 mg/L during each cycle.
- Salinity decreased from about 8 ppt in September to under 1 ppt in January. Salinity levels appear to remain low in the winter except for some spikes in concentrations that occurred during drain events conducted to leach salts from the soils.
- Water temperatures dropped from a high of about 20 degrees C in the September to about 8 degrees in January, beginning to recover after January 1.
- For this dataset, DOC concentrations correlations with methyl mercury and SUVA concentrations were statistically significant ($p=0.0000$) at the perimeter stations and predicted about 50 – 60% of the variance. For the interior stations, the correlations between DOC and methyl mercury were not as strong predicting about 30 – 36% of the variance. DO concentrations dramatically affected methyl mercury values. When DO concentrations for the discrete samples were > 4 mg/L at the perimeter sites, methyl mercury was typically below 0.2 ng/L. (DO concentrations within the discrete samples taken from the perimeter sites were either <0.5 or > 4 mg/L). For the interior stations, DO concentratons > 4 mg/L typically had f-meHg concentrations < 1 ng/L and u-meHg concentrations <= 2 ng/L. Below about DO levels of 3 mg/L, both unfiltered and filtered meHg increased dramatically. About one half the total meHg was in dissolved form.
- Wetland 123 exported about 2,5 – 3X the amount of DOC (306 and 826 mg/m2/inches of water/tide) and unfiltered meHg (31 and 117 ng/m2/inches of water/tide) than did Wetland 112. Regression plots suggest load exports were highest for when wetlands were managed to drain as compared to periods they were managed to flood or to maintain maintenance flows; however, those results were not always statistically significant. When considering water volumes being exported from the wetlands, about two times more water is exported from Wetland 123 than Wetland 112. This result is true for all water management objectives and for both fall and winter seasons. For this reason, total loads being exported per tide range from about four to ten times higher for Wetland 123 as compared to Wetland 112. The greatest differences are during the periods in which wetlands are managed to be drained. These estimates are standardized to wetland area.
- For the period during which comparable data was collected (October 2007 – January 2008), DOC concentrations were similar between Wetlands 112 and 123 as well as with Wetlands 525, 529 and 530. DOC concentrations within these wetlands were also higher than found in Montezuma Slough. From October through December, DOC concentrations in the wetlands were typically 2.5 – 7X higher than found in the slough. The data for methyl mercury was less complete. With the available data, it appears methyl mercury differed greatly temporally and spatially between the wetlands. Overall, methyl mercury values recorded at the wetlands were three times to an order of magnitude higher than values found in the slough.

Discussion

The ultimate objective of this manuscript is to develop recommended Management Practices (MPs) to improve the operation of managed managed wetlands in Suisun to minimize fall DO sags and the potential export of methyl mercury. These wetlands have been managed primarily to enhance waterfowl habitat. This section identifies several key discussion points and recommends actions and management practices (MPs) to better protect water quality.

Fall and Winter Flushing in the Context of Peytonia and Boynton Slough Water Quality: DO, DOC and Hg

Flushing occurs in the fall and winter at Wetlands 112 and 123. Both these events have their own objectives: fall flushing is conducted to accelerate decomposition of organic matter in order to reduce BOD loads to the sloughs; winter flushing is conducted to leach salts from the soils.

A distinguishing characteristic of the sloughs during the fall is low DO levels, occurring from mid September into mid December for both Boynton and Peytonia Sloughs. Net water flows during this time are upstream. These characteristics tell us fall Biological Oxygen Demand (BOD) exceeds oxygen (re)generation rates from upstream sources through diffusion, mixing or advection.

At the wetlands studied, fall flushing begins in late September and continues into October. Water is flooded onto the fields, drained and re-flooded. This process occurs over a couple weeks to a month depending upon a number of conditions (e.g. tides, wetland elevations, desired scheduling). The fall flushing events cause immediate DO sags as measured in the water at the perimeters of the wetlands, occurring immediately upon initiation of the drain event. DO is reduced to near 0 mg/L and these levels continue at some locations within the wetlands for days with little diurnal variation. After these events end, DO levels remain depressed in the wetlands suggesting chronic BOD problems.

Other water quality effects occur during these fall flushes. Large DOC concentration spikes occur during the flooding and draining of the fall flush. This trend occurred to some degree at both wetlands during initial fall flushes though the magnitude and the duration differed. (Secondary fall flushes appeared to increase DOC concentrations less. meHg can also spike during this time though this trend may be due to same processes promoting greater DOC transport into the water column or because of DO sags promoting methylation. Finally SUVA spiked during the first fall flush, though to different degrees in the different wetlands. This trends suggests more reactive DOC being exported during these first flushes.

During these fall flushing events, a DO response results in the sloughs. Discrete first flushes in the fall from Wetlands 112 and 123 led to DO sags in both Peytonia and Boynton Sloughs. The DO sags are about 2 mg/L for Wetland 112 drain events and about 5 mg/L for Wetland 123 drain events. DO concentrations in the sloughs sometimes drop near 0 mg/L and then remain depressed thereafter until early December. At that time, DO levels recover to above the standard of 7 mg/L December and remain so into mid April. These DO sags have been a chronic problem in Suisun during this time of year.

Winter flushing also causes DO sags within the wetlands and at some locations DO can drop near 0 mg/L. This study found these drops to be shorter lived than during the fall. Hg, DOC and SUVA stay low during these events. Importantly during the winter events DO sags caused by flushing do not greatly affect DO levels in the sloughs. DO levels in Boynton and Peytonia Sloughs drop by 1 – 2 mg/L but seldom dropped DO below 7 mg/L. During this period, net flows in the slough are in the downstream direction (See appendix G, tidal mixing).

In considering loading from wetland management, our data suggests the greatest DOC export occurs during the drain events. This result was not statistically significant ($p<0.05$). The wetlands on average exported about 550 mg DOC/m^2/inches of outflow/tide.

From these analyses, discrete winter flushing events are preferable to discrete fall events. Fall events appear to greatly diminish water quality whereas the winter events do not. DO drops in the fall are problematic in the sloughs into early November, slowly beginning to recover thereafter. Slough DO levels can recover quickly even in the fall in response to wetland water management. These analyses suggest flushing events be minimized in the fall to the extent practicable. Additionally, fall flushing events that are needed should export the least water volume and be asynchronous with flushes from other wetlands.

Managing Salinity

A secondary goal for managing the managed wetlands but also considered important for sustaining the lands is managing salinity. Maintaining lower soil salinity is targeted in order to increase the waterfowl habitat value of the managed Suisun wetlands. This goal is substantiated by area and regional data showing the higher habitat value of freshwater wetlands to waterfowl.

Water column salinity within the wetlands increases immediately with flooding. Initial water column salinity in the fall is about 8 – 10 ppt. Fall flushes do not seem to greatly reduce salinity though water column salinity does decrease through the fall. Winter flushing clearly removes salts from the soils. With each winter flush event, water column salinity levels spike. These spikes are very short lived with salinity returning to levels below 1 – 2 ppt.

Data suggests salinity flushing at Wetland 112 is more effective than at Wetland 123. By the third flushing event at Wetland 112 during the first winter, water column salinity is much lower than the earlier events. Salinity levels in the fall reaches a maximum of about 8 ppt. At Wetland 123, the last winter flushing event has a peak similar to the first peak and salinity levels the following fall are near 10 ppt. As discussed earlier, water quality effects to the sloughs are relatively minimal.

Comparing the results at Wetlands 112 and 123 suggests more winter flushing events can more effectively draw salts from the soils and lead to lower salinity levels in the wetland the following year. Other factors may be affecting salinity levels and the data set is limited.

Spatial and Temporal Differences in Management at the Wetlands and Possible Implications on Water Quality

Though these wetlands are managed to enhance waterfowl and duck habitat, these wetlands are not managed the same. Managed wetland management activities depend upon a number of factors including including the preferences of and resources available to wetland managers; wetland elevation relative to tide elevations; wetland infrastructure; and proximity to water sources. These factors result in differences between wetlands in their management activities. Such was the case for the wetlands here:

- Managers at Wetland 123 controlled weeds and prepped fields primarily through discing (20% acres) whereas at Wetland 112 herbicides and mowing (40% acres) were the primary tools; and
- Three drain-flood cycles were used over one month in the winter at Wetland 112 to leach salts from soils whereas at Wetland 123 two drain-flood cycles occurred over a 2 month period.
- Water volumes on and off Wetland 123 are typically about two times higher than for Wetland 112 during all seasons and for all water management objectives.

Management changes were also made from Year 1 to Year 2 to test the effect of first year recommendations on water quality. During both years, a flood-drain-flood event was used at the beginning of the season to accelerate biomass decomposition and reduce DOC export. DOC is released rapidly from plant litter upon flooding (Pellerin et al, 2010). During the second year, the period of the drain event was extended to over a week with the hypotheses that an extended damp period would promote more rapid decomposition of DOC. Longterm litter decomposition has been shown to depend upon hydroperiod and be higher for alternating periods of flooded and exposed litter (Conner and Day 1991; Battle and Gooladay, 2001). However, data and literature reviews by others show no consistent hydroperiod effects on biomass decomposition rates but instead the composition of the microbial community (e.g. fungae, bacteria) is predominantly effected (Day, 1983; Inkley et al, 2008). And data specific to hydroperiod effects on DOC export is even more sparse. Pellerin et al (2010) showed fresh litter rapidly releases DOC when inundated. Yet O'Connell et al (2000) found DOC released from forest litter was independent of its place in the floodplain and under different oxygen treatments.

When comparing Wetlands 112 and 123, several comparisons can be made with regard to water quality effects. First, DOC loads are estimated to be about 2.5X higher from Wetland 123 as compared to Wetland 112 by tide event when the data is standardized against wetland area and inches of water exported. This result is fundamentally due to generally higher DOC concentrations that occur during the early fall period of flooding when DOC concentrations begin to rise during the first flush, peak through the drain period and remain elevated. One possible reason for these higher concentrations may be the methods used to control weeds and prepare the land. At Wetland 123, discing is used to control weeds and prepare lands as compared to mowing and herbicides at Wetland 112. Discing causes greater disturbance than herbicide applications or mowing, and soil disturbance has been shown to accelerate DOC diffusion through greater oxidation and greater infiltration into the upper soil layers. Thus, this method of land preparation would be expected to increase DOC leaching from the soils. This land preparation may also explain the higher SUVA values that occur during the first flush at Wetland 123 as compared to Wetland 112.

Second, greater water volumes flow on and off Wetland 123 throughout the year for each tide event. Wetland 123 is adjacent to two sloughs and water can be more easily applied to Wetland 123 as compared to Wetland 112.

These factors together lead to estimated DOC loads to be about 4 – 10X higher on a per area and per tide basis for Wetland 123 as compared to Wetland 112. These increased loads affect DO levels in the sloughs when the wetlands are managed to be drained. The higher loads from Wetland 123 typically cause DO sags of about 5 mg/L whereas the sags associated with Wetland 112 are about 60% less (~ 2 mg/L). Interestingly the decreases in DO in the sloughs are triggered during the initiation of draining event though gross water exports from the wetlands are not always dramatically different as shown for Wetland 112. Importantly load exported from the wetlands does not necessarily remain in the sloughs. Water flows on and off the wetlands with changing tide elevations. Water transport imports and exports loads to and from the wetlands. Thus, both gross and net loads exported may need to be considered.

BOD of DOC

What is the lifetime of the labile component of exported DOC that is responsible for its high oxygen demand when it is first flushed into the sloughs? Biological Oxygen Demand was not measured in this study and other parameters such as SUVA and DOC are not reliable predictors (Krasner et al. 2009). SUVA was measured to characterize the reactivity of the DOC though Weishaar et al (2003) show SUVA is not necessarily a good predictor of reactivity. SUVA is a surrogate measurement of aromaticity with higher SUVA representing greater aromaticity . Aromatic organics (e.g. humic acids) tend to be more reactive than other organics (e.g. fulvic acids). Free electrons from the double bond ring structure enable these molecules to more readily react with other molecules. At the wetlands, SUVA becomes elevated immediately upon flooding and then remains so for about 2 – 3 weeks. However, the data regarding SUVA may provide relatively little information regarding BOD because, studies do not show a relationship between SUVA and BOD (Krasner et al 2009).

DO data from the wetlands may provide some insight. DO measurements at the interior stations show DO is near 0 mg/L into December. DO concentrations measured at the perimeter stations sag immediately in the fall with wetland draining and stay depressed into early December during which time the wetlands are managed under maintenance flow conditions. Under maintenance flow conditions, Wetland 112 exported an average of 75 – 120 mg/m2 of DOC per tide event and Wetland 123 exported 480 – 600 mg/m2 (Table 9). We presume all the wetlands in Suisun have DOC export rates in the range shown here.

These exports provide enough organic carbon with sufficient BOD to continue to suppress DO levels in the sloughs. During this period Boynton Slough typically has reverse flow in the upstream direction and Peytonia Slough is typically in the downstream direction (Enright, 2010). Regardless of the flow directions, both sloughs experience depressed DO levels in the fall (Figure 9). Thus, the organic matter exported has sufficient BOD to chronically suppress DO levels in the sloughs below the water quality standard.

These data suggest minimizing load export in the fall by minimizing water exports should help keep DO from dropping to near 0 mg/L. This approach could be achieved by reducing as practicable fall the first flush period in the fall as well as minimizing synchronous discharges into the sloughs from several wetlands.

Tertiary Treated Wastewater from FSSD – How to best utilize

Treated wastewater is high quality source water for these wetlands: DO is relatively high, mercury is low, DOC and BOD are low. Currently, this water is used to assist with flooding their fields. During the fall approximately 110 – 125 ac-ft is required to initially saturate the soils at Wetlands 112 and 123 and another 200 – 250 ac-ft are required at Wetland 123 and another 35 – 50 ac-ft are required at Wetland 112. FSSD discharges about 16 – 19 cfs (32 – 38 ac-ft/d) during the fall.

During each drain event, Wetland 123 has a net discharge of about 260 ac-ft over a period of about 7 days for about 37 ac-ft/d (Bachand et al. 2010). Wetland 112 has a lower net discharge during these drain events of about 75 ac-ft of 4.5 days for about 16 ac-ft/d. If sufficient water can be secured to flood the fields, diverting all FSSD tertiary treated wastewater into sloughs may be a way to help manage DO sags. DO drops immediately in the sloughs during drain events. Increasing other sources of water into the sloughs during that period may help meet the BOD needs in the sloughs at those times and minimize the periods in which DO drops to 0 mg/L and stays there for days at a time.

Conclusion

For this study, two managed wetlands (i.e. Wetlands 112 and 123) were studied. Beginning in late September, these two managed wetlands are flooded, drained and reflooded again as a kick-off to duck season. Water levels are then maintained relatively constant under quasi-steady state conditions until around February at which time the wetlands are drained and reflooded two or three times to leach salts from soils. In late spring, the fields are drained again to allow summer agricultural activities in support of waterfowl habitat.

All drain events from the two wetlands studied immediately depressed DO concentrations at the wetlands and triggered DO sags in the sloughs. During the fall, DO concentrations in the wetlands were near or at zero mg/L during these drain events and remained so for days at a time with little diurnal variation. DO concentrations in the sloughs also dropped near 0 mg/L remained depressed below the regulatory standard into early December. At this time, DOC, SUVA and meHg were generally elevated on the wetlands with highest concentrations spiking during the initial flood and (first) flush period. Winter DO sags from wetland drain events also occurred but baseline DO concentrations are higher at that time of year and higher flows are occurring in the winter were much higher and thus the DO sags were less consequential.

The DO sags likely occur for a number of reasons: exported low DO water from the managed wetlands along the sloughs, the biological oxygen demand of the released DOC, and the amount of dilution from higher DO water. In the fall, reverse flows likely exacerbate DO levels while in the spring high flows likely help to replenish DO.

DO may also be causing meHg problems. MeHg concentrations tended to be highest when DO concentrations were under 1mg/L and they dramatically decreased with increasing DO such that at above 4 mg/L DO filtered and unfiltered meHg were below 0.5 ng/L.

Both wetlands used different land management practices to control weeds and prepare for hunting season. Wetland 123 relied primarily on discing and Wetland 112 relied primarily on mowing. Wetland 123 typically had higher meHg, DOC and SUVA concentrations. Other factors may explain those differences but the different land management practices may contribute.

DOC and u-meHg exports were estimated for the two wetlands. Wetland 123 had greater water circulation rates (~ 3 times higher) than Wetland 112 and generally higher DOC and u-meHg concentrations. Those two factors led to Wetland 123 exporting 4 – 10 times more DOC and u-me Hg than Wetland 112. We calculated export rates from regressions and estimated that Wetland 123 exported an average 826 mg-DOC/m^2 and 31 ng-u-meHg/m^2 per tide event as opposed to 306 mg-DOC/m^2 and 117 ng-u-meHg/m^2 at Wetland 112 (Table 8). Importantly, all that export does not necessarily stay in the sloughs. Tide events push water and their associated loads on and off the wetlands. Thus, some exported loads from an ebb tide return onto the wetlands during a subsequent flood tide. Nonetheless, the effects of these loads can be seen in the sloughs. The typical drainage event from Wetland 112 suppressed DO concentrations in the sloughs by approximately 2 mg/L wherea from Wetland 123 DO sags by about 5 mg/L for Wetland 123 (Figure 9).

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Figures

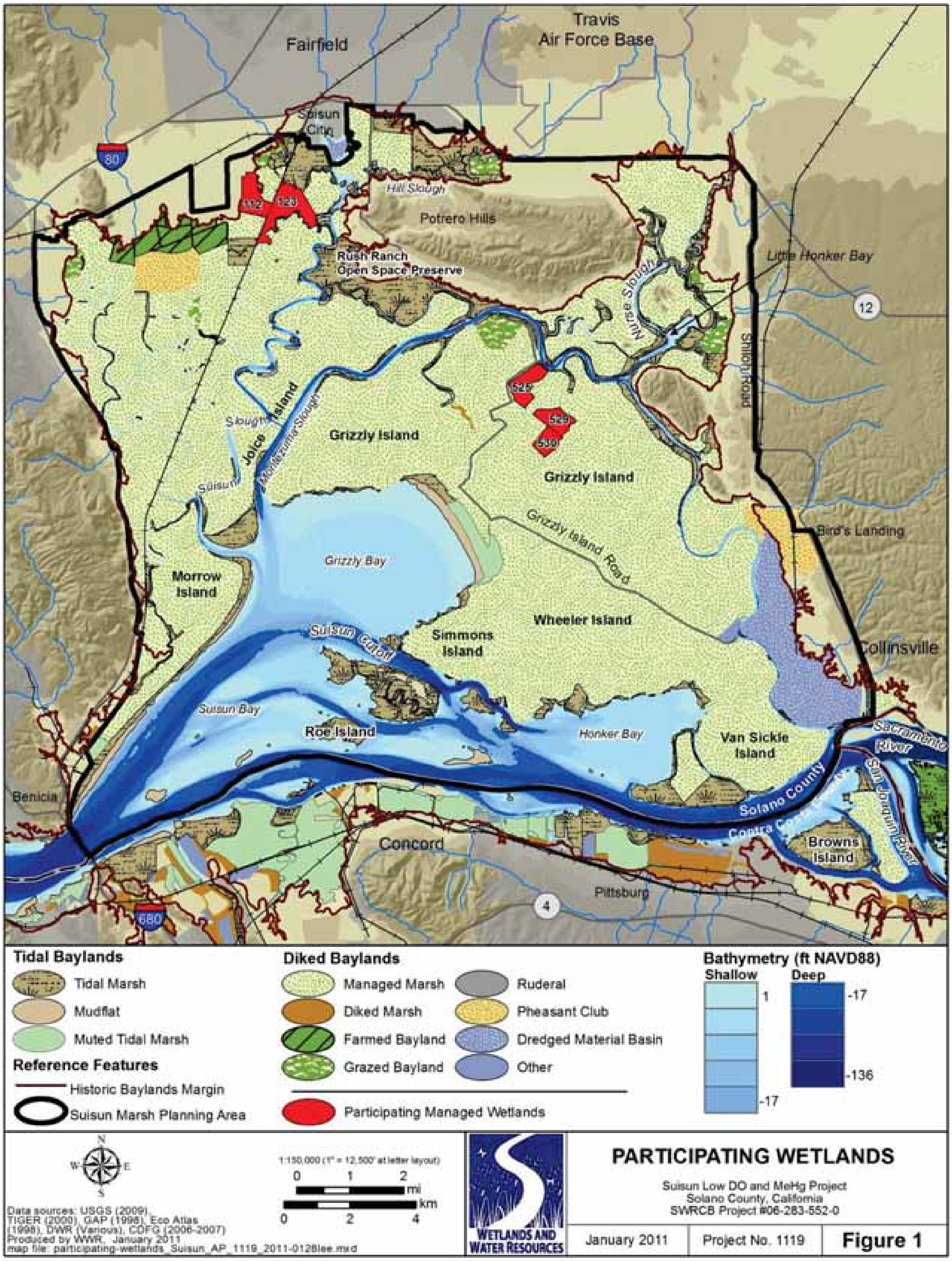


Figure 1. Map of Suisun Wetlands and Identification of Sites

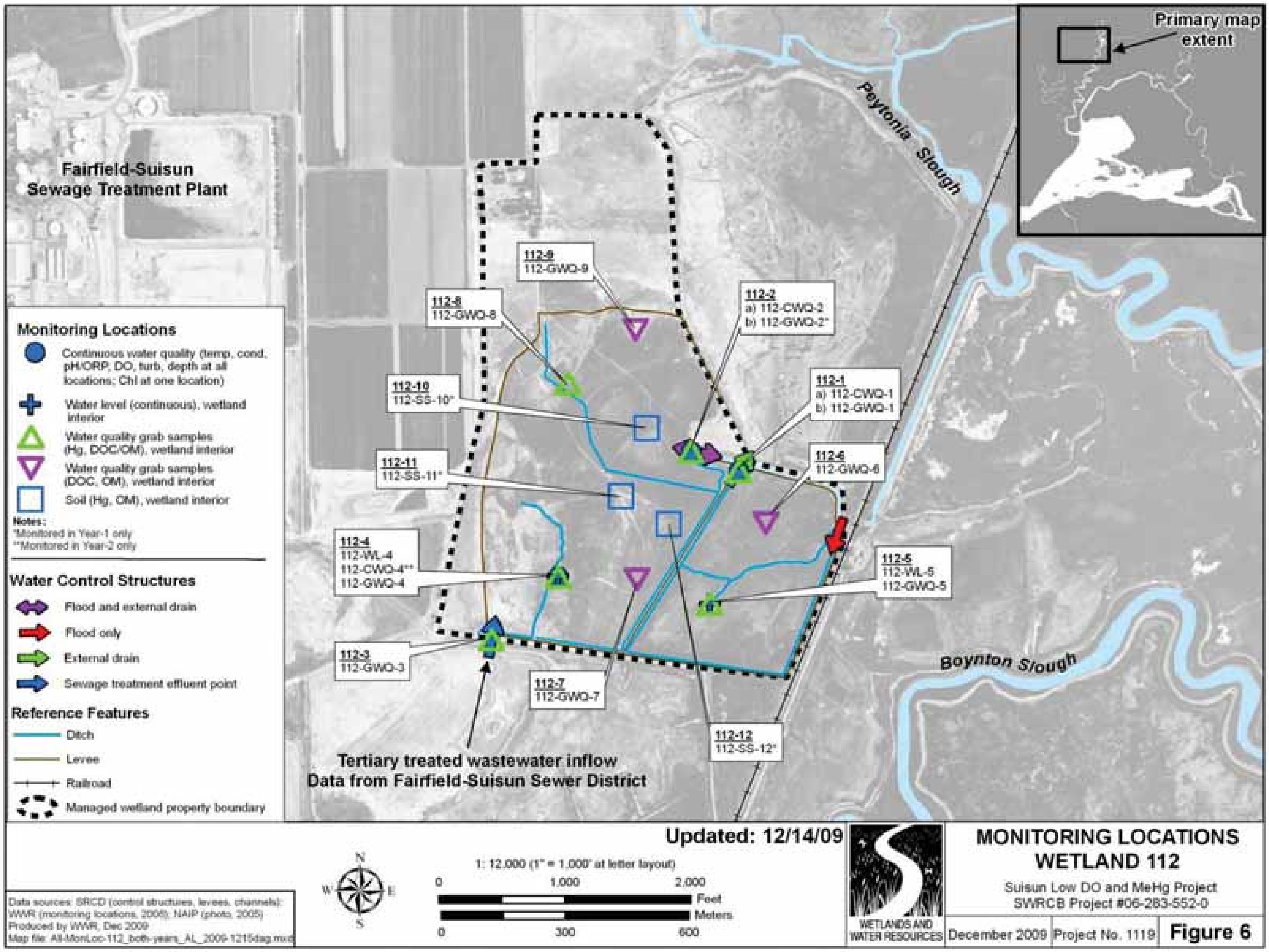


Figure 2. Wetland 112

Figure 3. Wetland 123

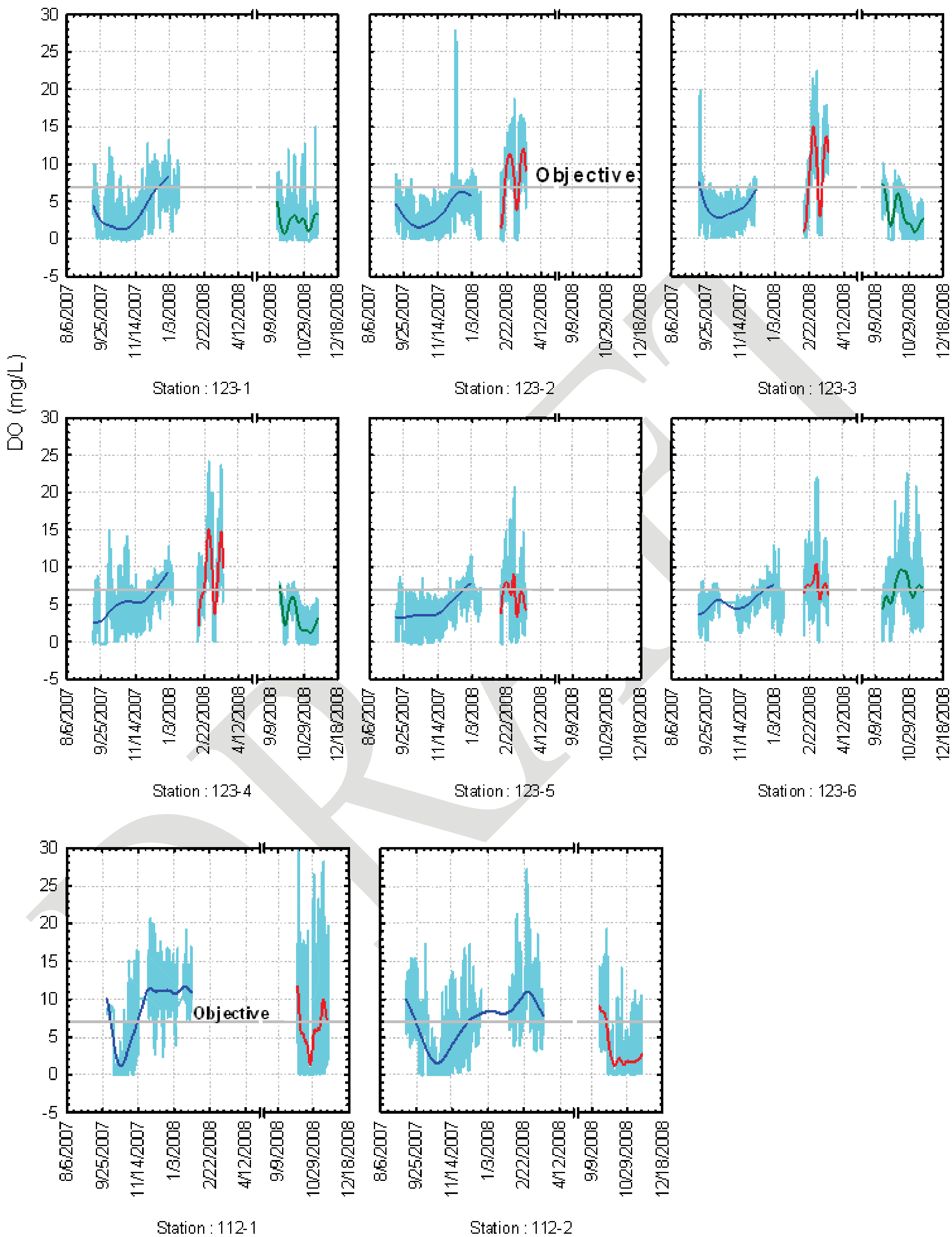


Figure 4. Temporal Dissolved Oxygen Trends at Perimeter Stations For Wetlands 123 And 112

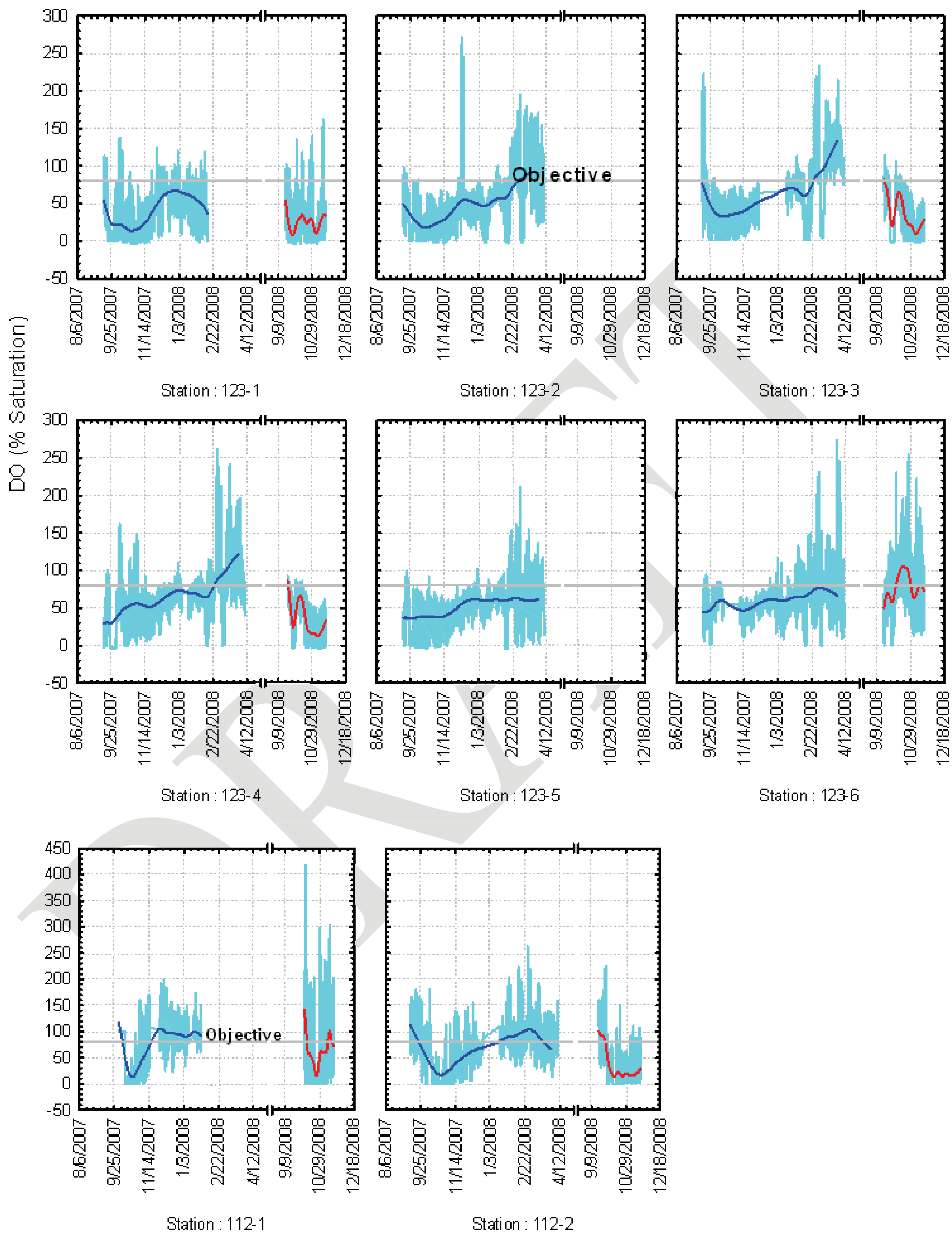
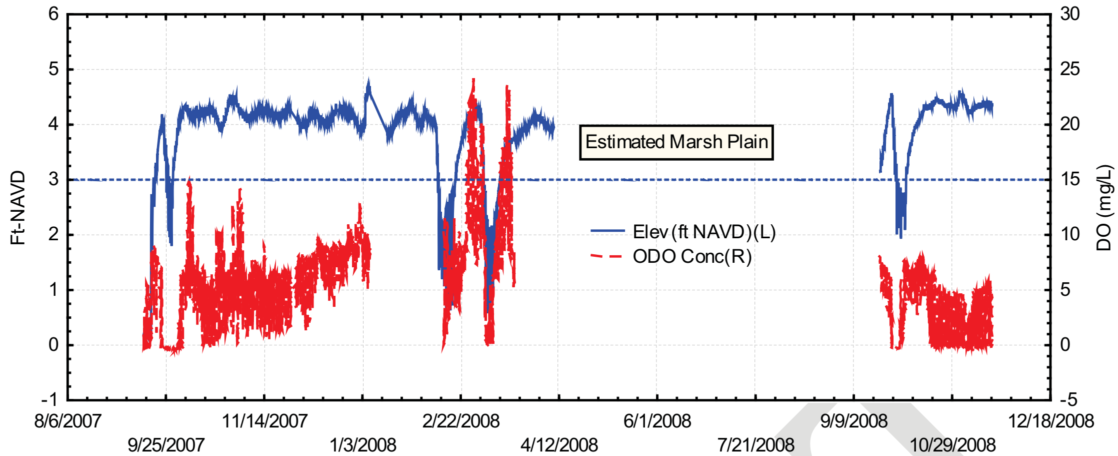
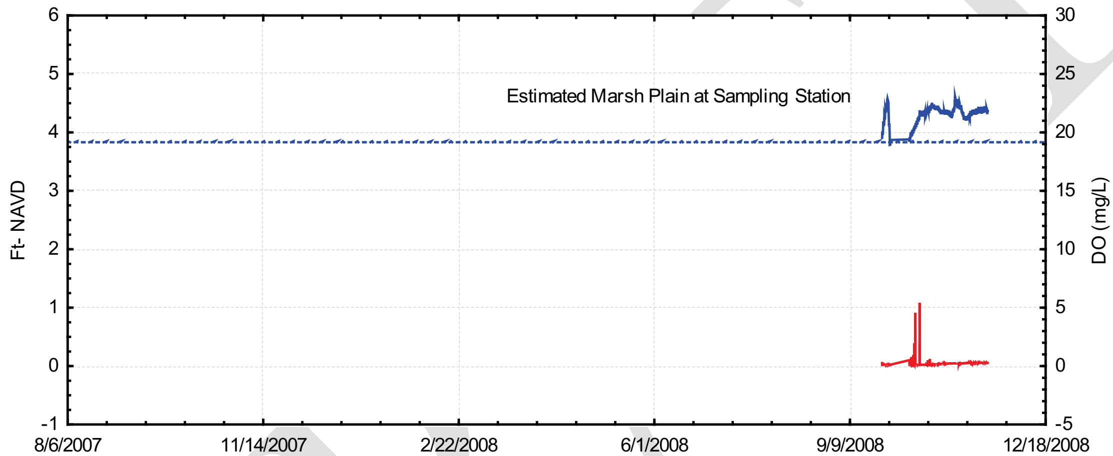


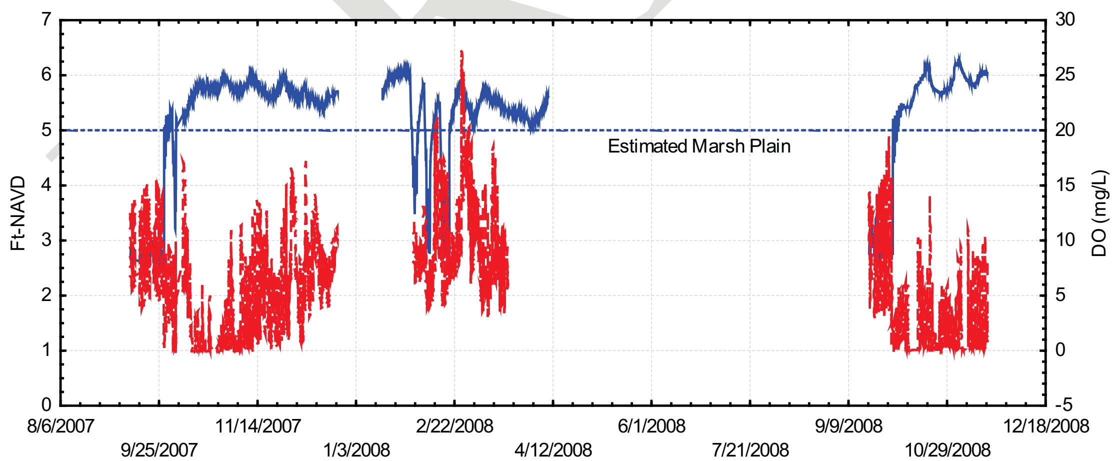
Figure 5. Temporal Dissolved Oxygen Percent Saturation Trends At Perimeter Stations For Wetlands 123 And 112



A. Station 123-4, Perimeter Site



B. Station 123-8, Internal Site



C. Station 112-2, Perimeter Site

Figure 6. Temporal Elevation Changes At Selected Perimeter Stations For Wetlands 123 And 112

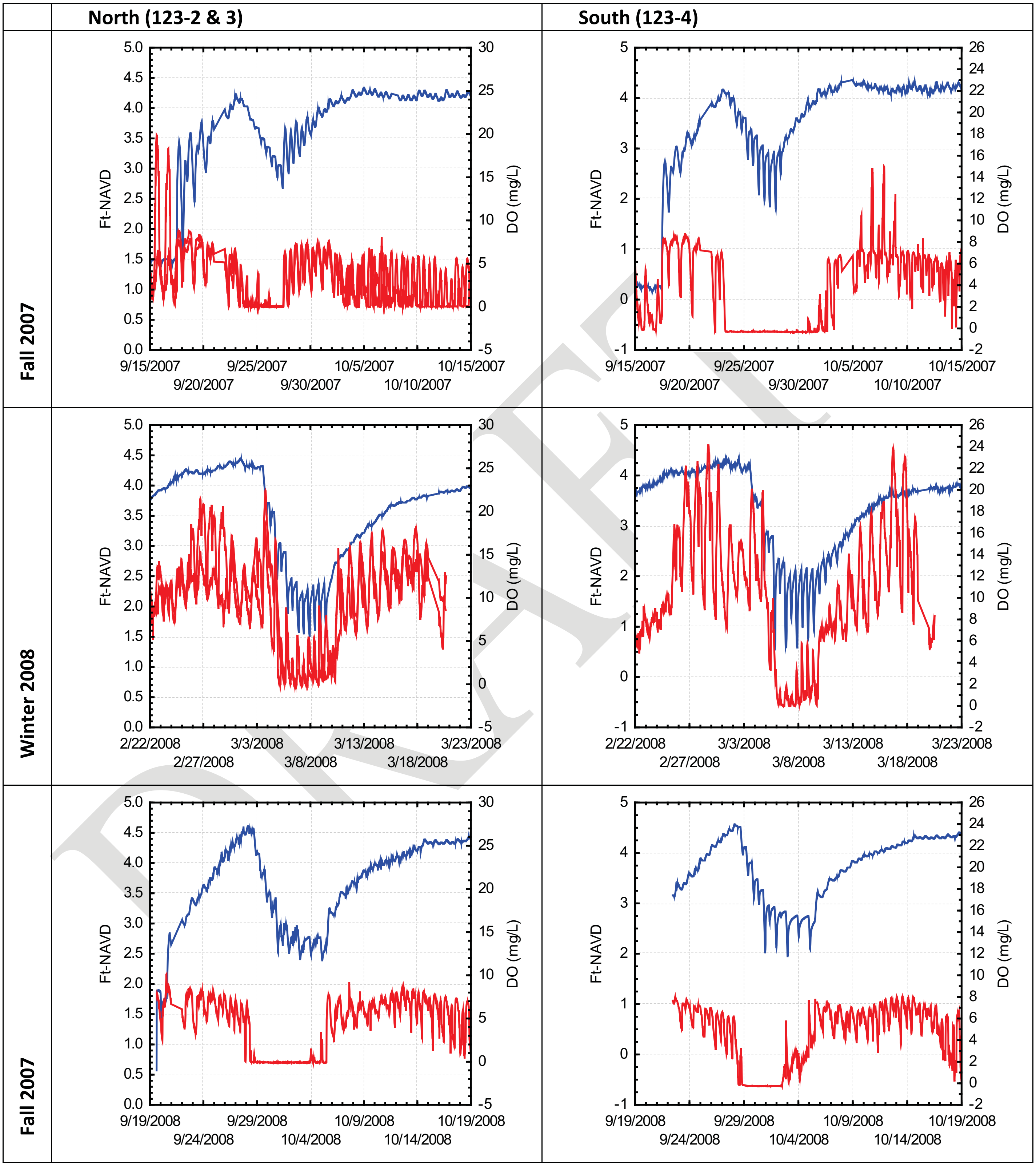


Figure 7. DO responses to Water Elevation Changes at Station 123-4.

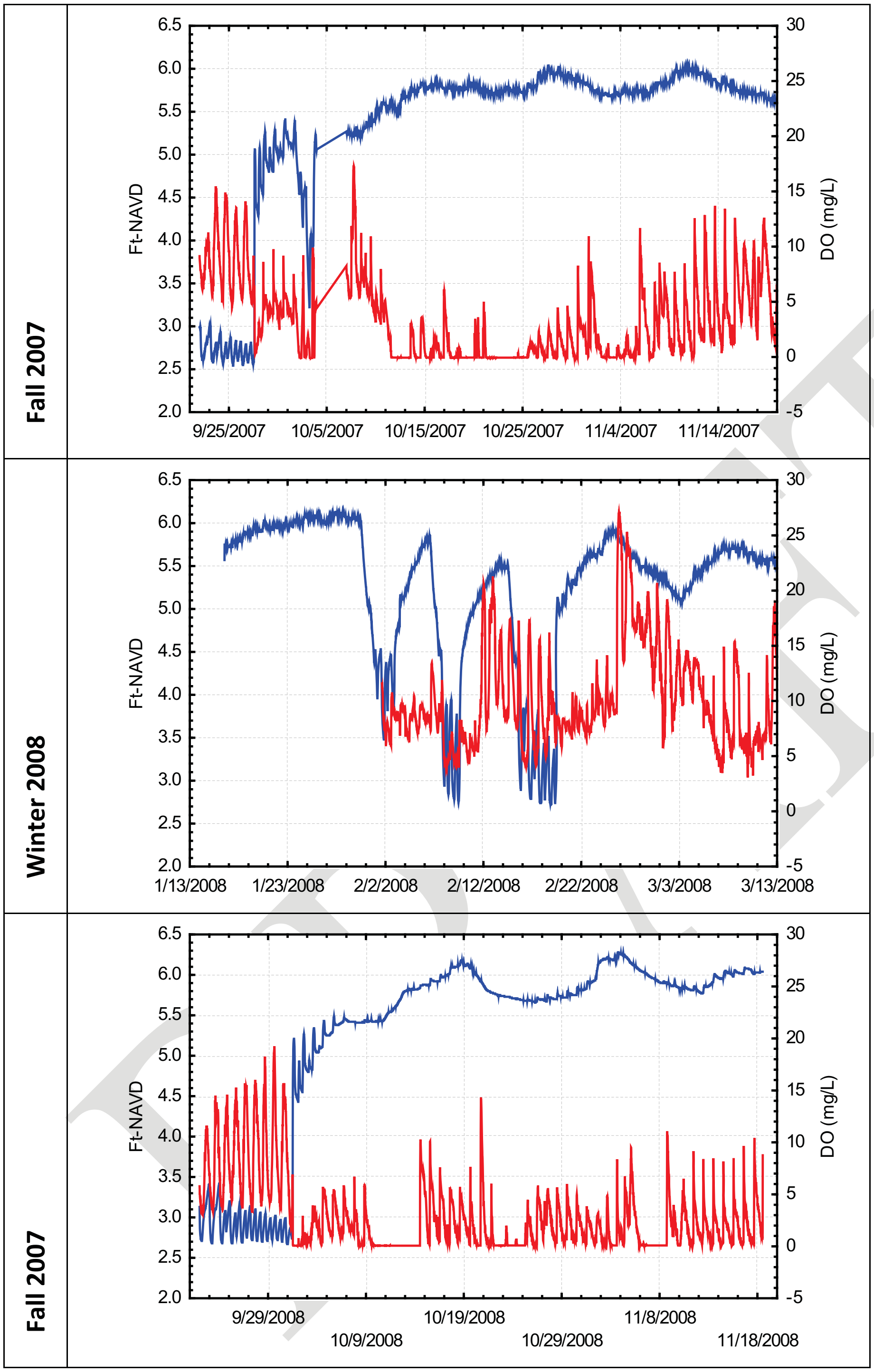


Figure 8. DO responses to Water Elevation Changes at Station 112-2.

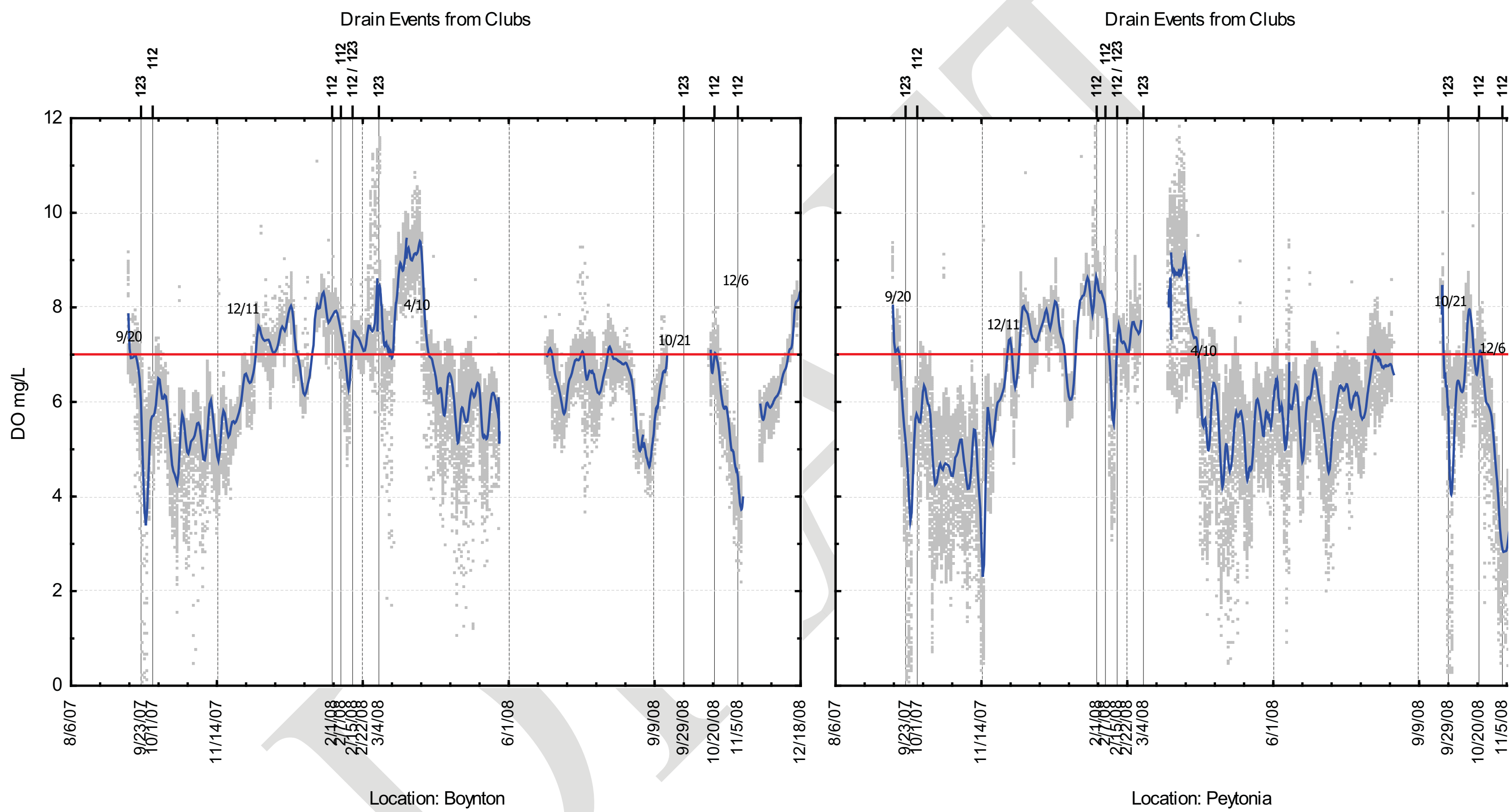


Figure 9. DO Concentrations in Boynton and Peytonia Sloughs

DO data shown is 15-minute data. Top axis gridline (black) identifies when a drainage event occurs from a wetland and the axis labels the wetland from which the event occurred. DO water quality is 7 mg/L and is identified with the red line. Dates on graph shows when the blue fitted DO line (negatively weighted exponential fit) crosses above or below the water quality standard.

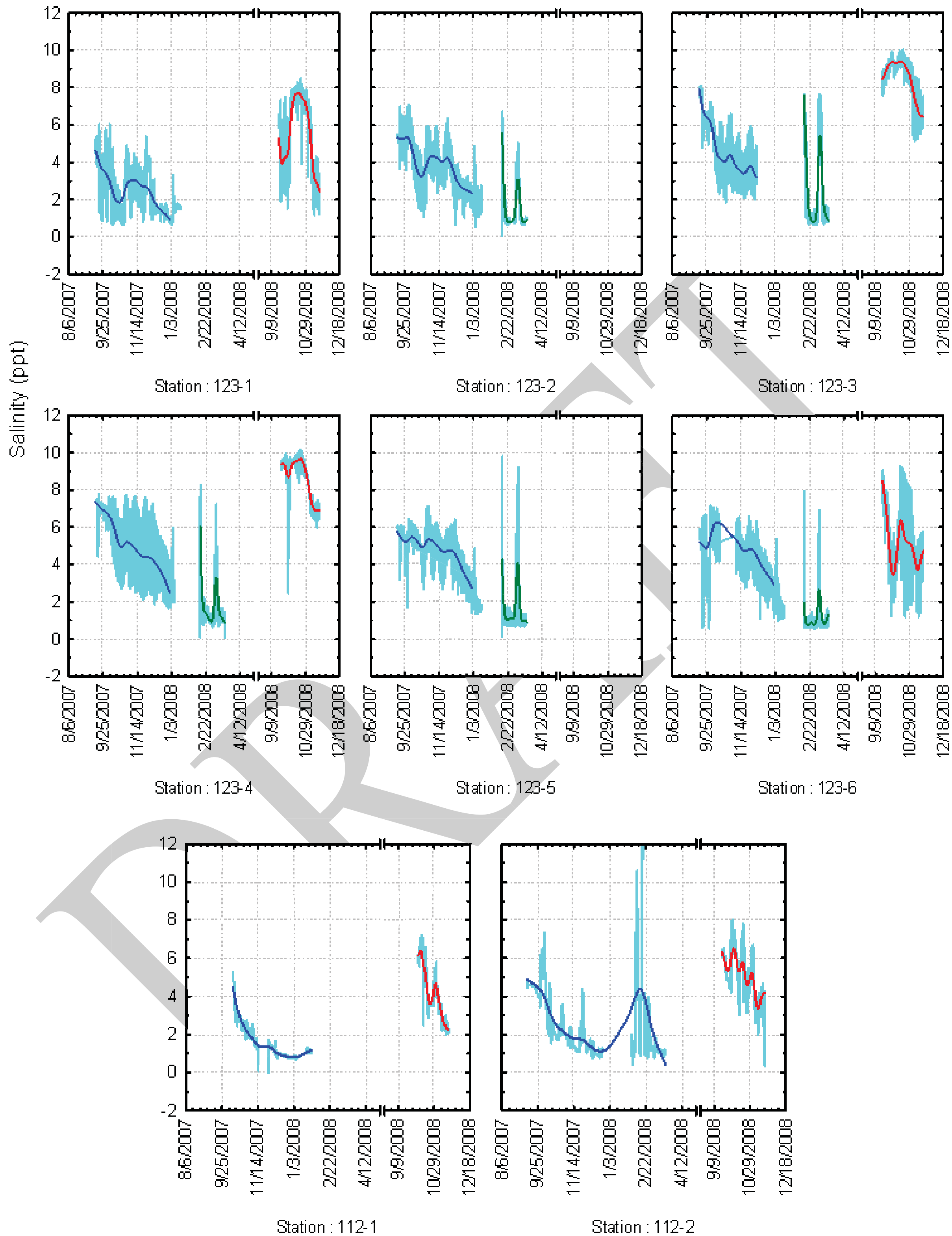


Figure 10. Temporal Salinity Trends At Perimeter Stations For Wetlands 123 And 112

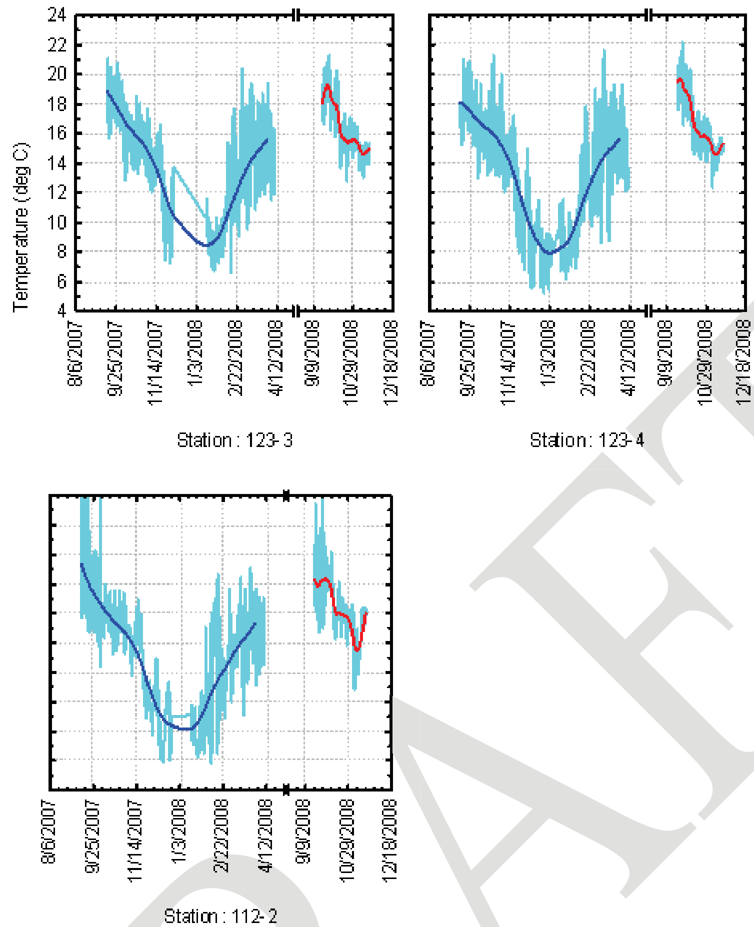


Figure 11. **Temporal Temperature Trends At Selected Perimeter Stations For Wetlands 123 And 112**

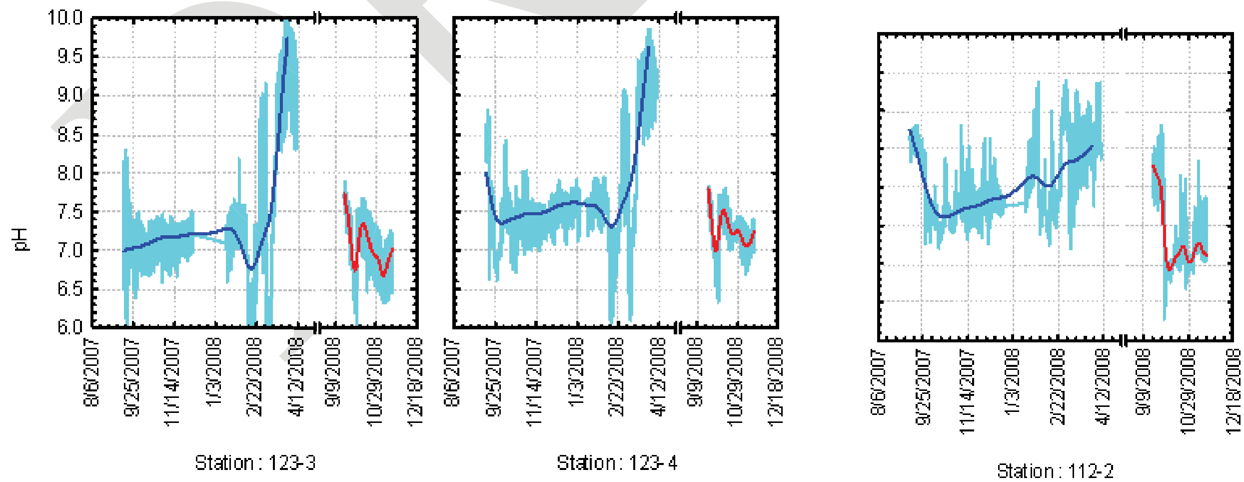


Figure 12. **Temporal pH Trends At Selected Perimeter Stations For Wetlands 123 and 112**

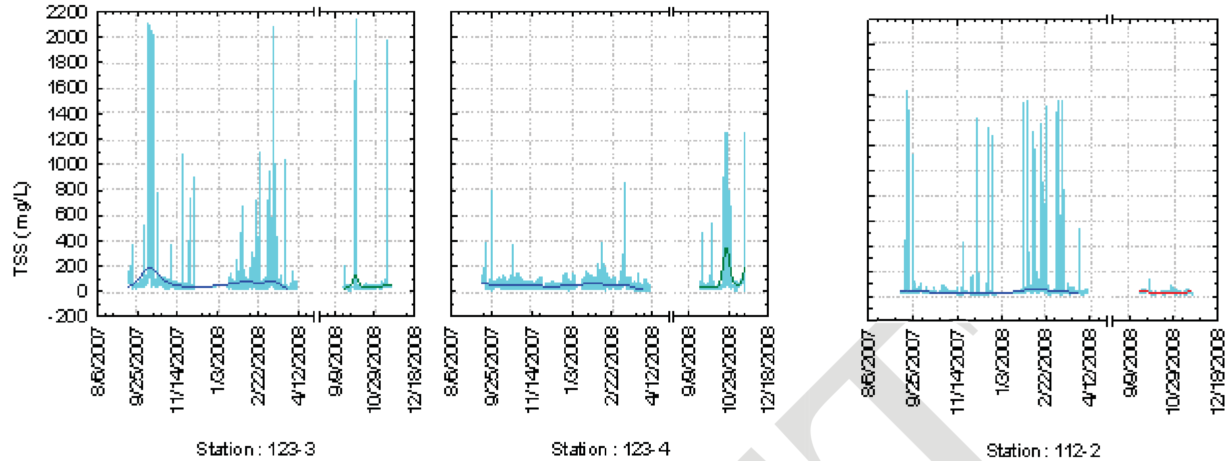


Figure 13. Temporal TSS Trends At Selected Perimeter Stations For Wetlands 123 And 112

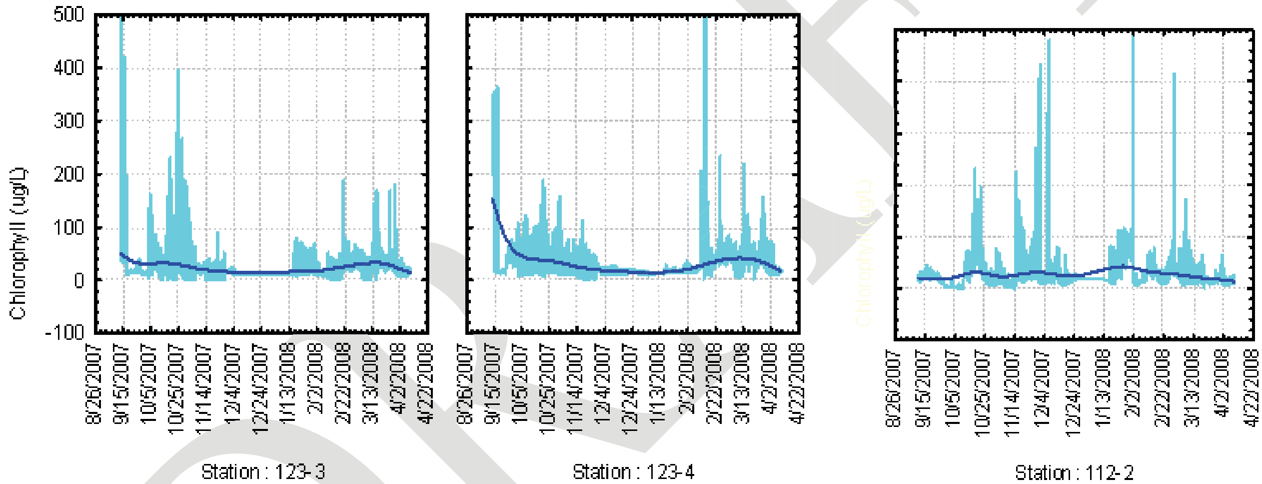


Figure 14. Temporal Chlorophyll Trends At Selected Perimeter Stations For Wetlands 123 And 112

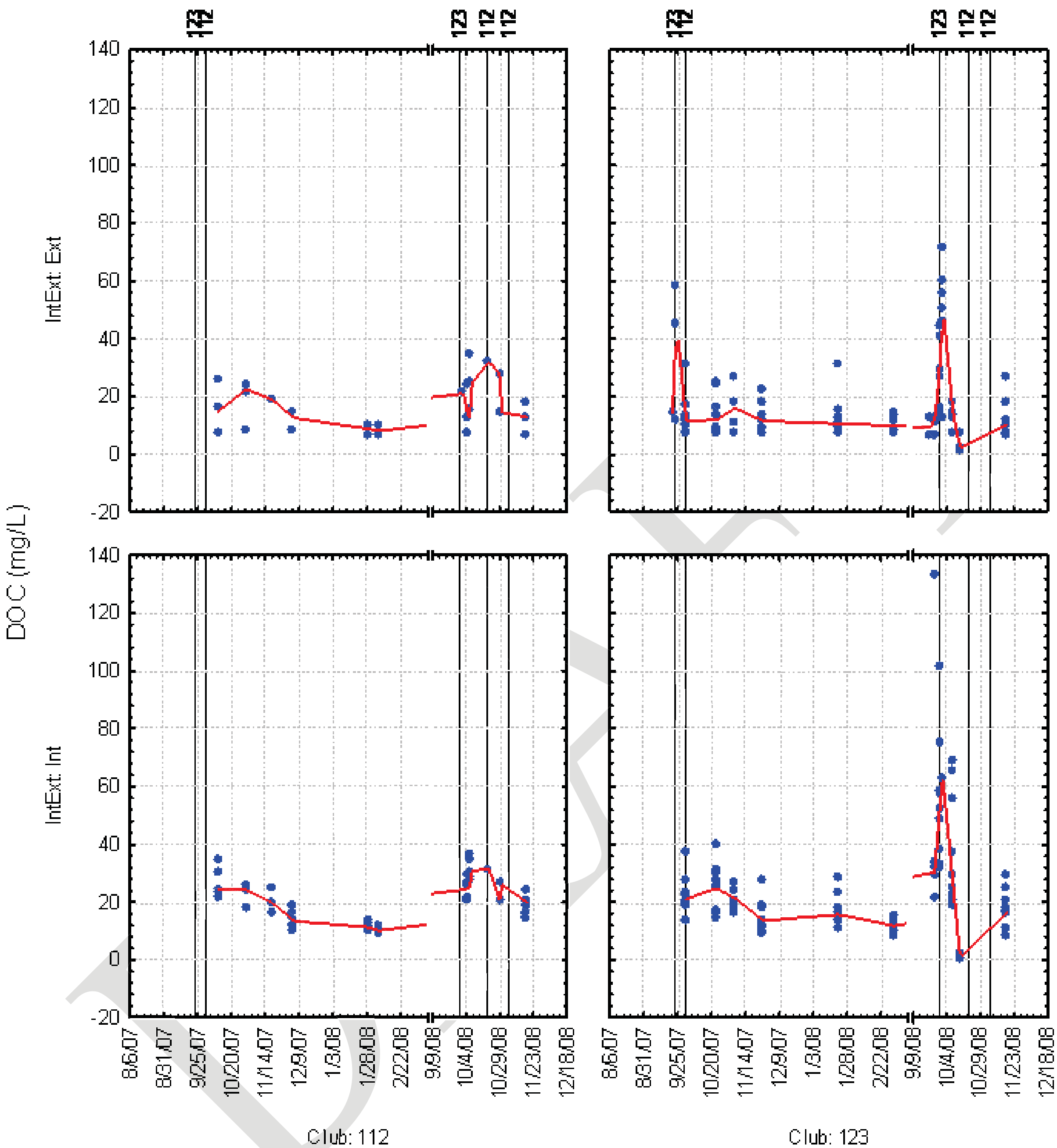


Figure 15. Changes in DOC at Wetlands 112 and 123 perimeter and interior stations.

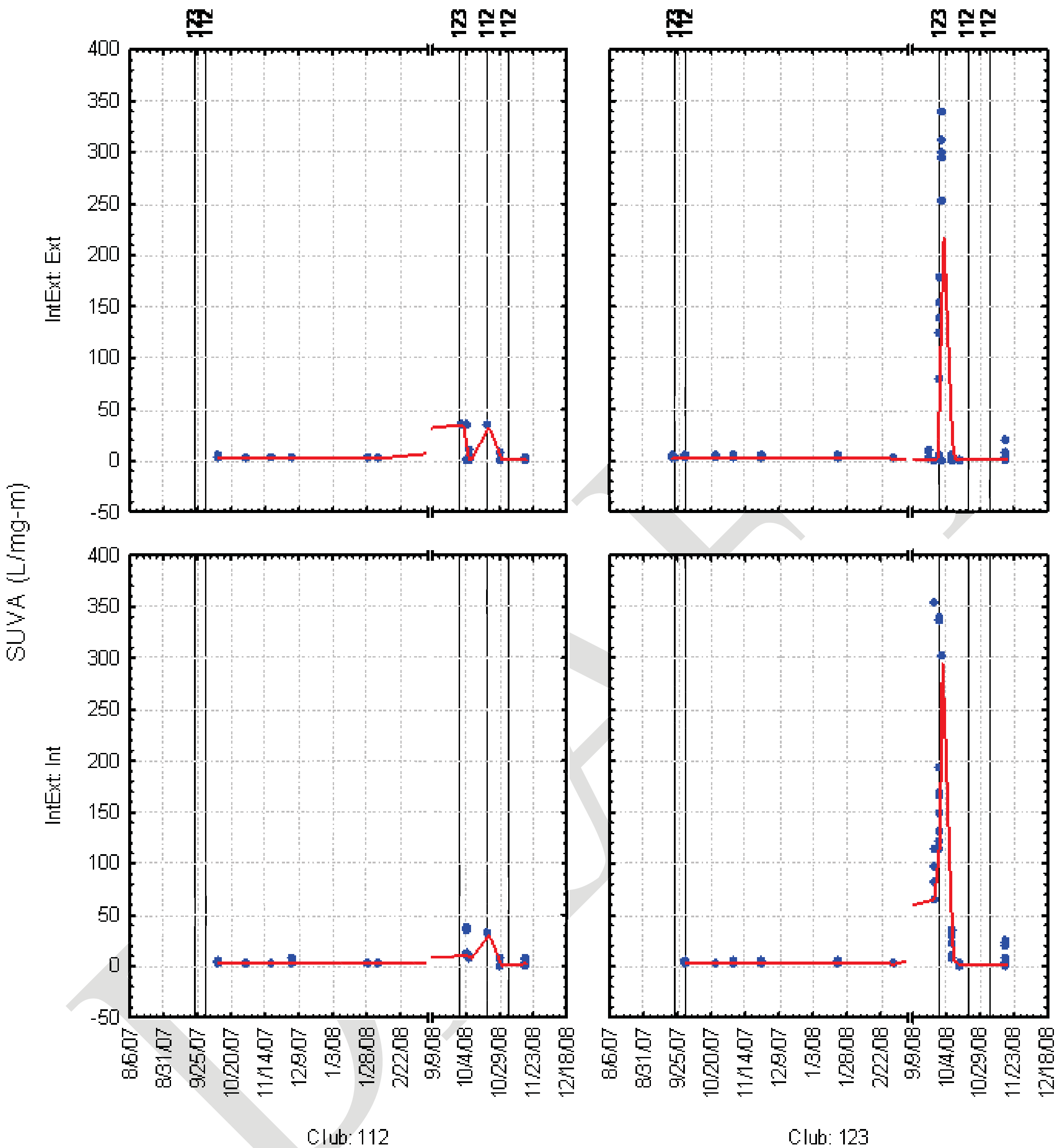


Figure 16. Changes in SUVA at Wetlands 112 and 123 perimeter and interior stations.

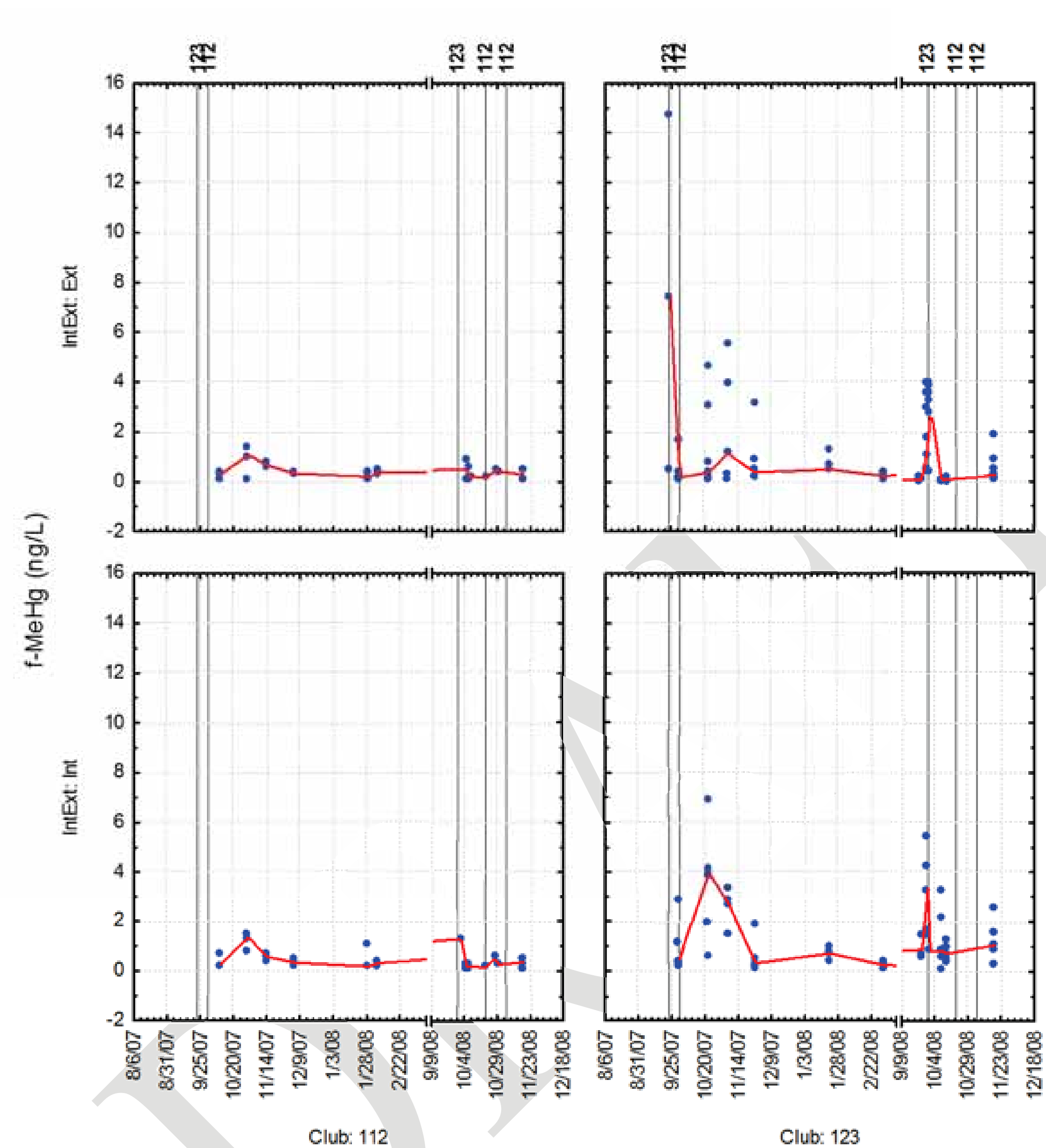


Figure 17. Changes in filtered meHg at Wetlands 112 and 123 perimeter and interior stations.

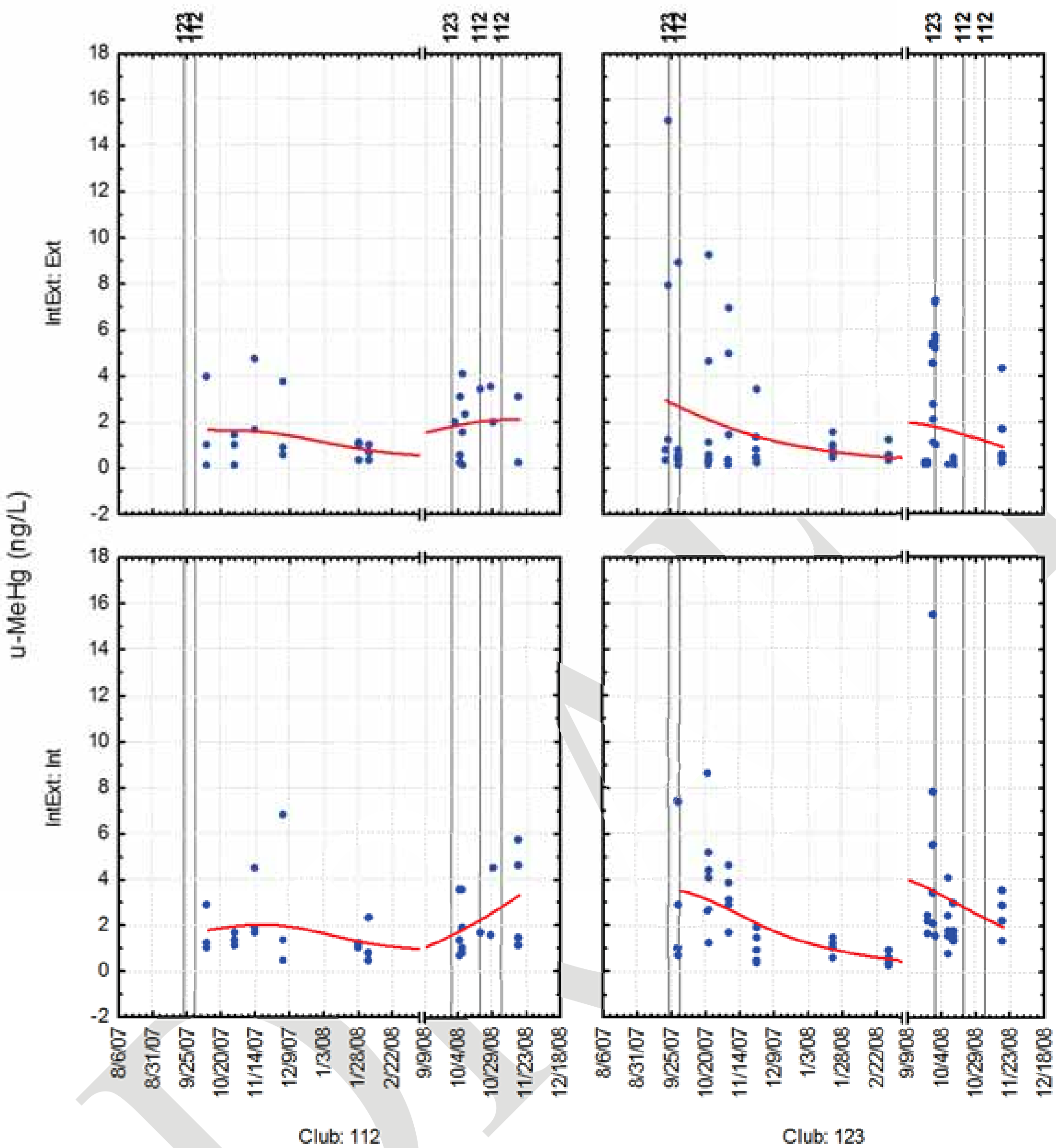


Figure 18. **Changes in unfiltered meHg at Wetlands 112 and 123 perimeter and interior stations.**

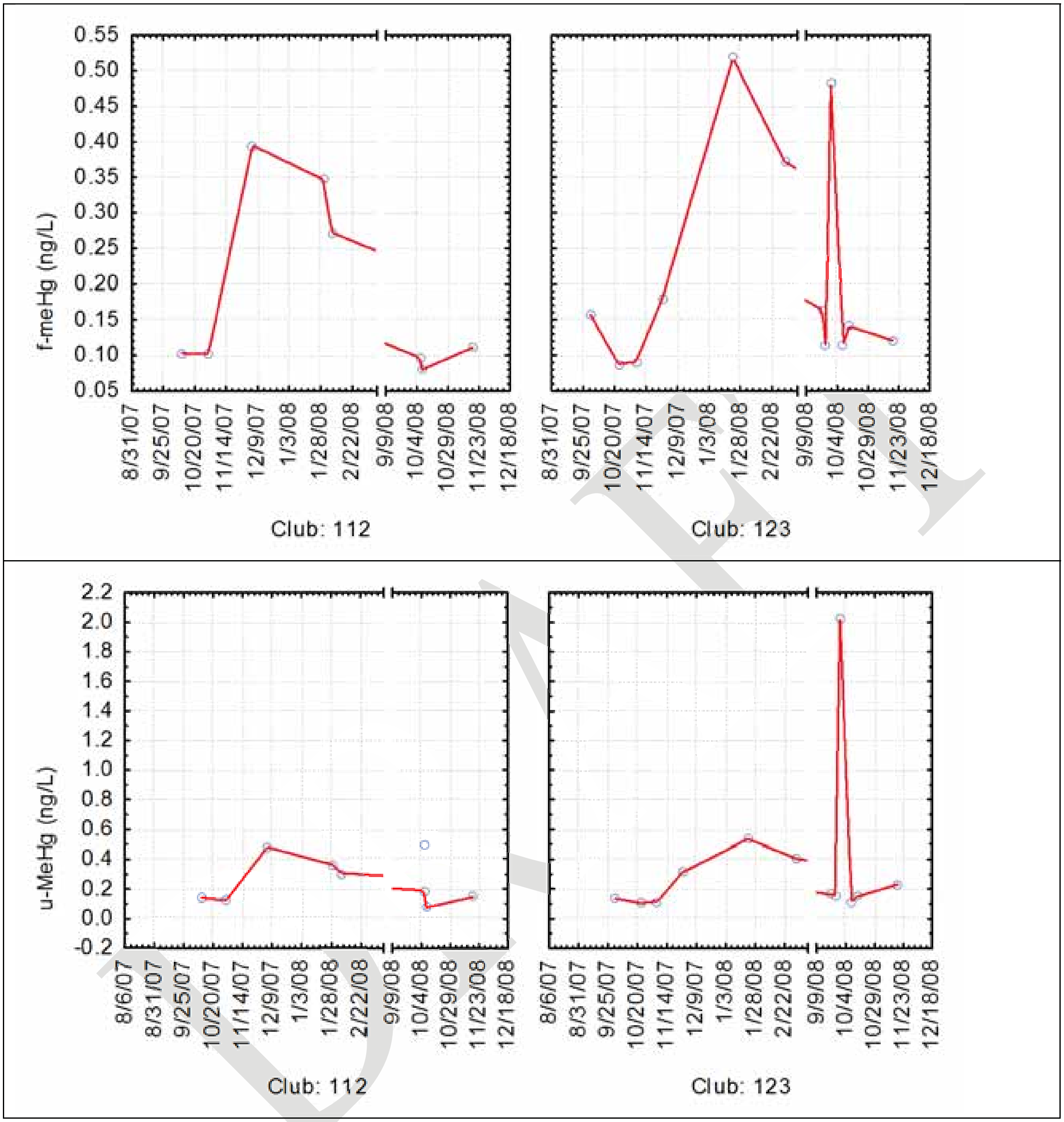


Figure 19. **Methyl mercury over time at Wetland 112 and 123 wastewater outflow locations**

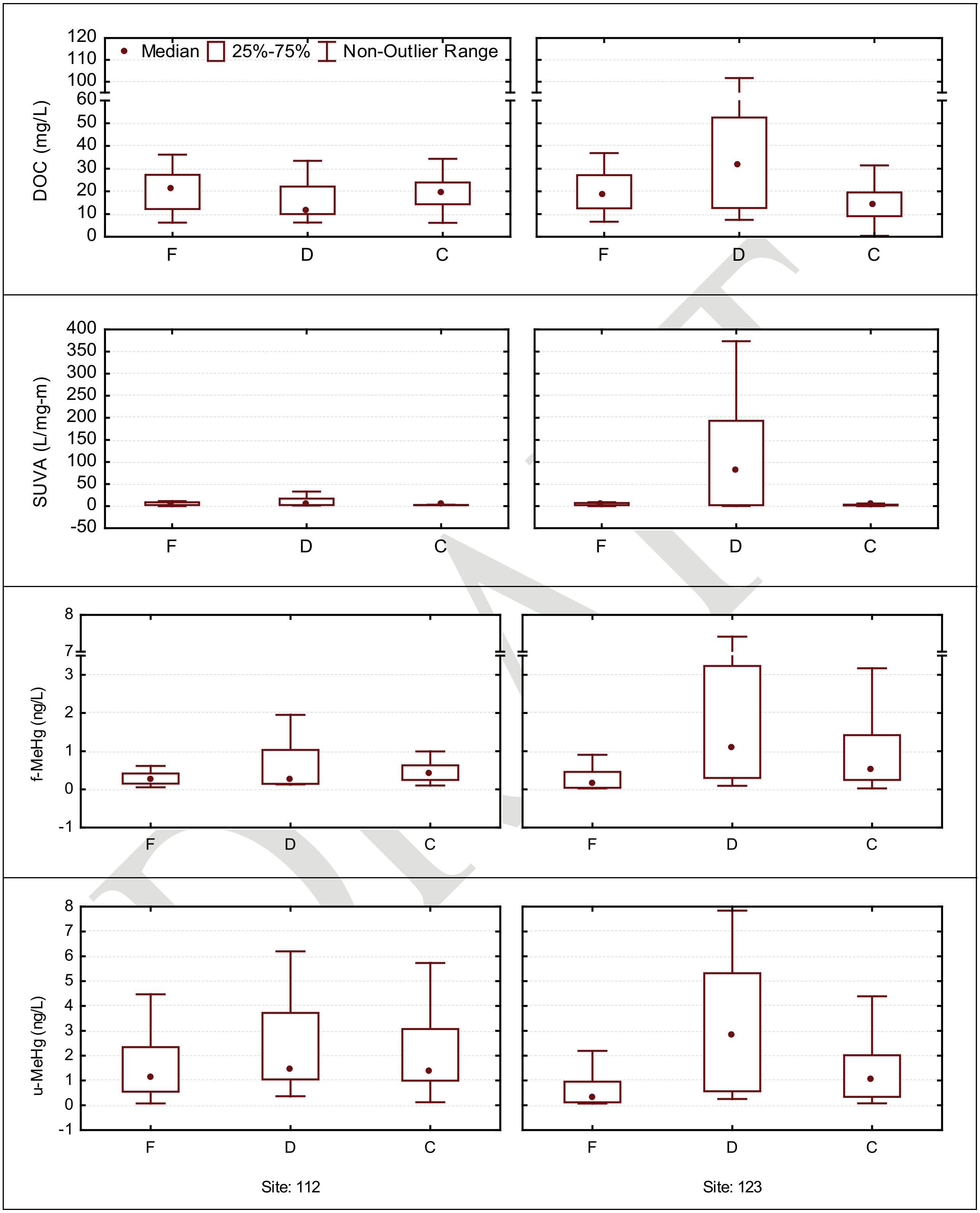


Figure 20. **Differences in median concentrations of key analytes at Wetlands 112 and 123 during flood, drain and continuous maintenance flow conditions.**

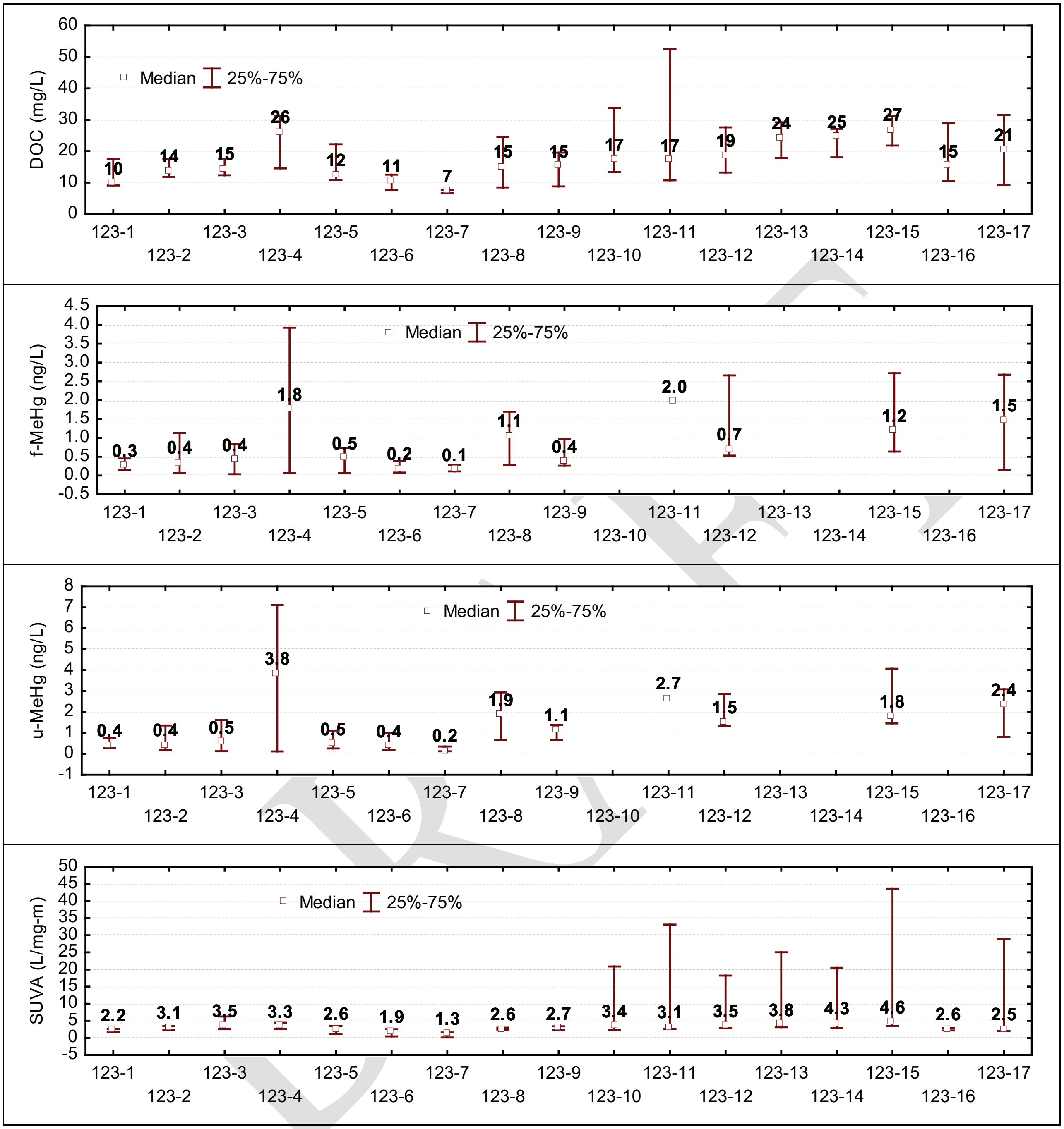


Figure 21. Median DOC , meHg and SUVA data at Wetland 123, September 2007 through December 2008.

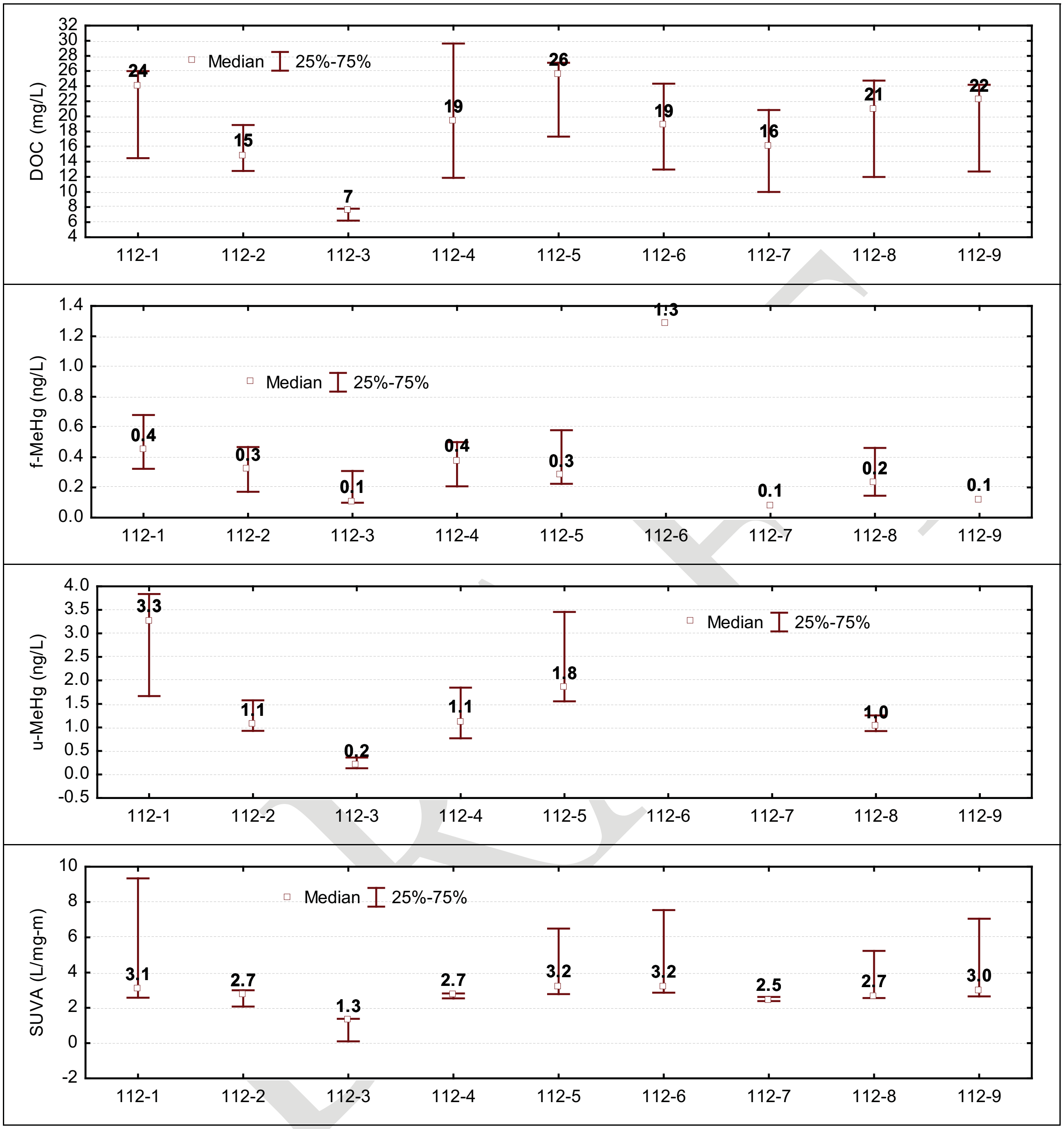


Figure 22. **Median DOC , meHg and SUVA data at Wetland 112, September 2007 through December 2008.**

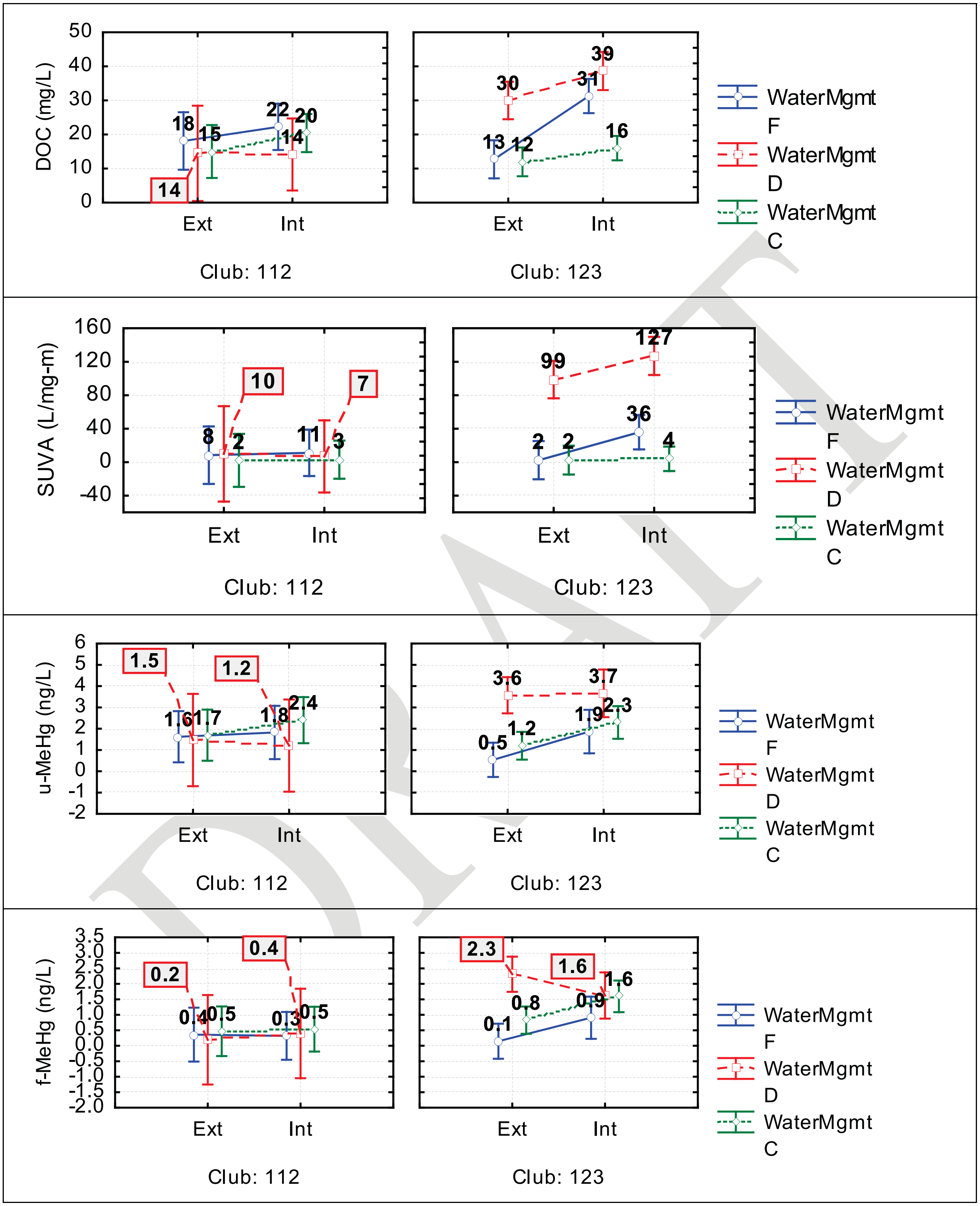


Figure 23. Mean Differences in water quality characteristics between internal and external perimeter sites at Wetlands 112 and 123.

Lines represent 95% confidence interval.

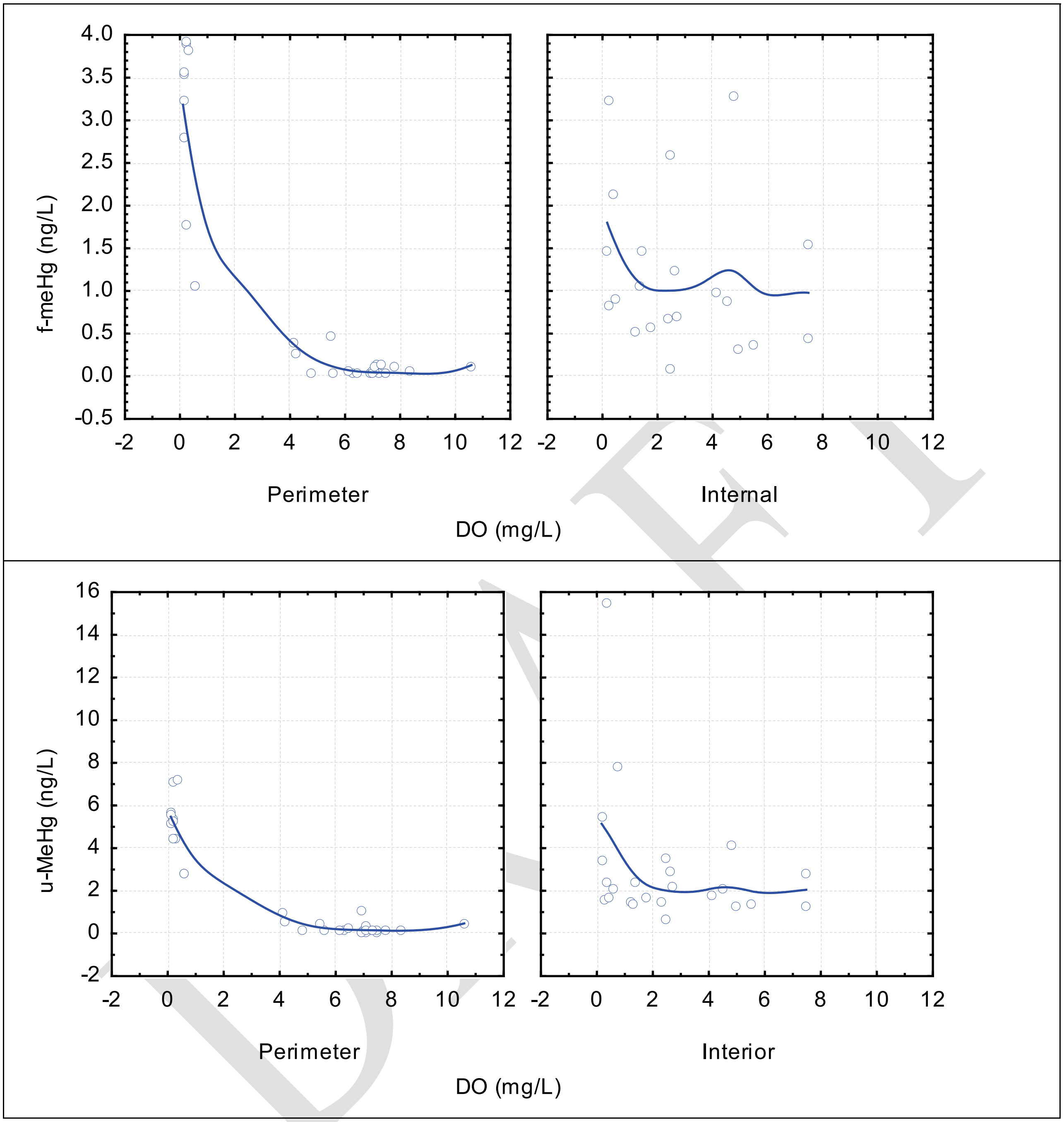


Figure 24. Filtered and unfiltered meHg v DO for perimeter and interior sites.

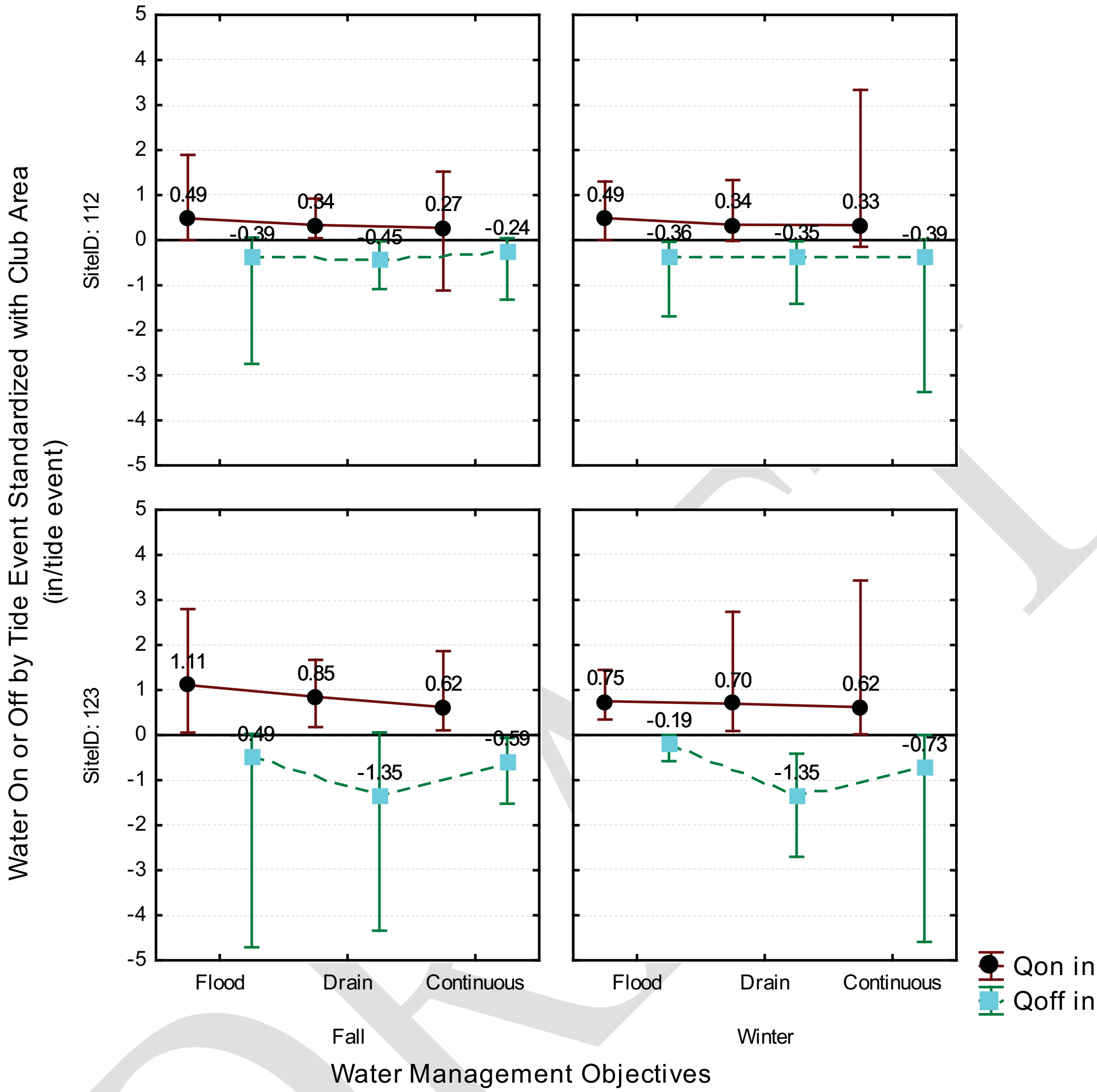


Figure 25. Average, Min and Max Water on and off by tide event for different water management objects during the fall and winter seasons at Wetlands 112 and 123.

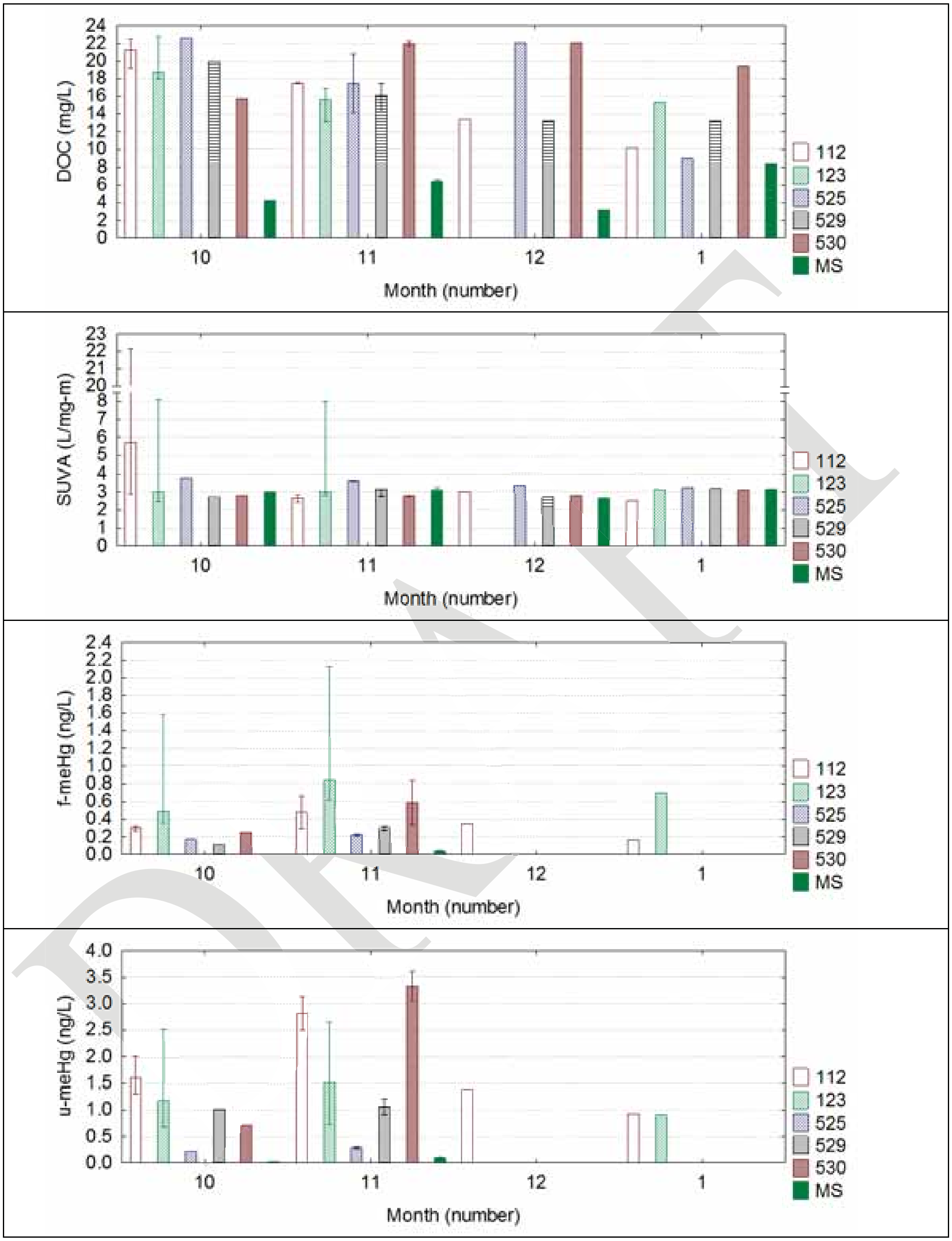


Figure 26. Comparing Water Quality Constituents throughout the sampling area.

Figure shows median values and 25th and 75th percentile (bars) by month using a single value per sampling data at each site. For Wetlands 112 and 123, perimeter station sampling values were averaged by sample date to get a single value for the wetland.

Tables

Table 1. Northwest Clubs: Interior Sample Location Characteristics

Club	Station	WCS [1]	Soil [4]	Vegetation	Elevation (ft NAVD88) [3]	Depth range at shoot level (ft) [2]	Landscape Position: At WCS	In Perimeter ditch [2]	In/influenced by marsh channel or swale	In interior Marsh plain	Near sewage effluent point	Management Setting: Mowed	Disked	Chemical Treatment	NA
112	112-1	24" fbr/flap	An	Open water/ tules	2.3	3.2 - 3.7	X	X						X	
112	112-2	36" combo/combo	An	Open water/ tules	1.1	4.4 - 4.9	X	X						X	
112	112-3 [5]	24" open pipe	An	NA-effluent outfall box	NA	NA	X				X				X
112	112-4	none	An	Pickleweed/annual grasses/bare	5.1	0.4 - 0.9			X	X	X	X			
112	112-5	none	An	Pickleweed/annual grasses/bare	4.2	1.3 - 1.8			X			X			
112	112-6	none	An	Smartweed/pickleweed	5.0	0.5 - 1.0				X		X			
112	112-7	none	An	Pickleweed/annual grasses	5.1	0.4 - 0.9				X		X			
112	112-8	none	An	Pickleweed/annual grasses	4.7	0.8 - 1.3			X			X			
112	112-9	none	An	Annual grasses/saltgrass/pickleweed	5.4	0.1 - 0.6				X					X
112	112-10	none	An	Pickleweed/annual grasses	4.4	1.1 - 1.6				X		X			
112	112-11	none	An	Pickleweed/annual grasses	5.0	0.5 - 1.0			X			X			
112	112-12	none	An	Annual grassess/pickleweed/smartweed	4.8	0.7 - 1.2				X		X			
123	123-1	36" fbr/flap	Ta	Open water/ tules	NA	NA	X	X							X
123	123-2	36" fbr/combo	Ta	Open water/ tules	0.1	3.9 - 4.4	X	X							X
123	123-3	36" fbr/combo	Sp	Open water/ tules	-0.6	4.6 - 5.1	X	X							X
123	123-4	36" fbr/combo	Sp	Open water/ tules	-0.3	4.3 - 4.8	X	X							X
123	123-5	24" combo/combo	Sp	Open water/ tules	-1.5	5.5 - 6.0	X	X							X
123	123-6	24" combo/combo	Sp	Open water/ tules	-0.5	4.5 - 5.0	X	X			X				X
123	123-7 [5]	36" with valve	Sp	NA-effluent outfall box	NA	NA	X				X				X
123	123-8	none	Sp	Smartweed/swamp timothy/annual grasses	3.4	0.6 - 1.1			X						X
123	123-9	none	Sp	Watergrass/smartweed	3.3	0.7 - 1.2				X					X
123	123-10	none	Sp	Smartweed/swamp timothy/annual grasses	2.9	1.1 - 1.6				X		X			
123	123-11	none	Sp	Smartweed/swamp timothy/annual grasses	3.2	0.8 - 1.3			X	X		X	X		
123	123-12	none	Sp	Smartweed/masrh aster/watergrass	2.9	1.1 - 1.6			X				X		
123	123-13	none	Sp	Alkali bulrush/watergrass/cocklebur	2.9	1.1 - 1.6			X					X	
123	123-14	none	Sp	Smartweed/swamp timothy/annual grasses	2.5	1.5 - 2.0				X					X
123	123-15	none	Sp	Smartweed/swamp timothy/annual grasses	2.1	1.9 - 2.4			X	X					X
123	123-16	none	Sp	Smartweed/swamp timothy/annual grasses	3.4	0.6 - 1.1				X	X	X			
123	123-17	none	Sp	Watergrass/smartweed/cocklebur	3.1	0.9 - 1.4				X	X	X			
123	123-18	none	Sp	Smartweed/swamp timothy/annual grasses	2.5	1.5 - 2.0			X	X		X			
123	123-19	none	Sp	Smartweed/swamp timothy/annual grasses	3.1	0.9 - 1.4			X	X			X		
123	123-20	none	Sp	Smartweed/swamp timothy/annual grasses	2.9	1.1 - 1.6			X	X					X

1 FBR = flashboard riser, flab = flap gate, combo is combination screw gate / flap gate. data entry is of format: pipe diameter (inches), inboard structure/outboard structure

2 112 shoot level = 5.5-6.0 ft NAVD88; 123 shoot level = 4.0-4.5 ft NAVD88

3 Elevation at perimeter (borrow ditch) stations are taken from bottom of YSI stilling wells. The actual channel bed elevation will be lower.

4 USDA Soil Type (MUSYM): An = Alviso silty clay loam, TA = Tamba mucky clay, SP = suiusn peaty muck.

5 Treated Wastewater Effluent Point

Table 2. Wetland Management

Club	Year	Month	Dryland Activities			Water Management Activities						
						Management goal			Management action			
			Mow-ing [1]	Discing	Spraying	Salt leaching	Vegetation Irrigation	Waterfowl use	Flood	Pre-flood [2,3]	Drain	Circulate
123	Pre-Study	Oct-06						x				x
		Nov-06						x				x
		Dec-06						x				x
		Jan-07						x				x
		Feb-07				x		x	x		x	
		Mar-07				x		x	x		x	
	Year 1	Apr-07			125 ac.			x				
		May-07										
		Jun-07										
		Jul-07										
		Aug-07	5 ac.	60 ac.								
		Sep-07						x	x	x	x	
		Oct-07						x				x
		Nov-07						x				x
		Dec-07						x				x
		Jan-08						x				x
		Feb-08				x		x	x		x	
		Mar-08				x		x	x		x	
	Year 2	Apr-08			120 ac.			x				
		May-08										
		Jun-08										
		Jul-08										
		Aug-08	5 ac.	60 ac.								
		Sep-08						x	x	x	x	
		Oct-08						x				x
		Nov-08						x				x
		Dec-08						x				x
		Jan-09						x				x
		Feb-09				x		x	x		x	
		Mar-09				x		x	x		x	
112	Pre-Study	Oct-06						x	x		x	x
		Nov-06						x				x
		Dec-06						x				x
		Jan-07						x				x
		Feb-07				x		x	x(3)		x(3)	
		Mar-07				x		x				
	Year 1	Apr-07			25 ac.			x			x	
		May-07					x	x	x(2)		x (2)	
		Jun-07					x	x	x(2)		x	
		Jul-07					x	x			x	
		Aug-07										
		Sep-07	80 ac.					x		x		
		Oct-07						x	x		x	x
		Nov-07						x				x
		Dec-07						x				x
		Jan-08						x				x
		Feb-08				x		x	x(3)		x(3)	
		Mar-08				x		x				
	Year 2	Apr-08			25 ac.			x			x	
		May-08					x	x	x (2)		x (2)	
		Jun-08					x	x	x (2)		x	
		Jul-08					x	x			x	
		Aug-08										
		Sep-08	80 ac.					x				
		Oct-08						x	x	x	x	x
		Nov-08						x				x
		Dec-08						x				x
		Jan-09						x				x
		Feb-09				x		x	x (3)		x(3)	
		Mar-09				x			x		x	

1 Mowing in 2007 was done with rotary deck mower. Mowing in 2008 was done with flail mo

2 Pre-flood is a preliminary wetting of the marsh plain before full fall flood-up to saturate th
establish flow paths on the marsh plain, and accelerate the decomposition of dead organi

3 The pre-flood at Club 123 in 2008 was followed by a 6 day drying period

Table 3. Discrete Water Quality Data Summary, Fall 2007 through Winter 2008.

Constituent	Units	N	Mean	Confidence -95%	Confidence +95%	Median	Min.	Max.	Lower Quartile	Upper Quartile	SD
DOC	mg/L	301	20.4	18.5	22.2	16.1	0.4	132.9	10.8	24.9	16.0
SUVA	L/mg-m	301	24.6	17.0	32.2	2.9	0.1	373.5	2.3	4.7	67.2
MeHg (f)	ng/L	225	1.0	0.7	1.2	0.4	0.0	14.7	0.2	1.0	1.6
MeHg (u)	ng/L	228	1.9	1.6	2.2	1.1	0.0	15.5	0.4	2.8	2.3
SSC	mg/L	123	16.9	13.9	19.9	11.9	-1.0	96.1	6.4	22.1	16.6
DO	mg/L	85	3.4	2.7	4.1	2.5	0.1	11.5	0.4	6.5	3.2
NTU		85	25.6	21.9	29.2	22.4	2.5	85.6	13.7	33.5	17.0
pH		85	6.9	6.8	7.0	6.8	5.7	8.8	6.5	7.3	0.5
SC	mS/cm	84	11.8	10.6	12.9	14.0	1.6	18.6	7.5	16.2	5.2
Temp	deg C	85	17.4	16.8	18.0	17.6	12.3	27.4	15.2	19.0	2.9

Table 4. 3-way ANOVA Analyses for Wetland (123 v 112), Interior v. perimeter site and Water Management Regime (flooded v. drained v. maintenance flow).

	Treatments	DOC	SUVA	f-MeHg	u-MeHg
Primary	WaterMgmt	0.0039	0.0000	0.0788	0.1279
	IntExt	0.0022	0.2341	0.4773	0.1626
	Site	0.0061	0.0000	0.0008	0.1977
Factorial	WaterMgmt*IntExt	0.2625	0.6237	0.5881	0.5985
	WaterMgmt*Site	0.0002	0.0000	0.0929	0.0163
	IntExt*Site	0.0941	0.2415	0.6839	0.4081
	WaterMgmt*IntExt*Site	0.1836	0.6427	0.4186	0.8645

Table 5. Correlations between water quality constituents

	DO	DOC	f-MeHg	u-MeHg	SUVA	UV-254
Internal Stations						
DO Conc	1.00	-0.47	-0.18	-0.29	-0.49	-0.48
DOC	-0.47	1.00	0.41	0.58	0.82	0.79
u-MeHg	-0.29	0.58	0.69	1.00	0.52	0.63
Perimeter Stations						
DO Conc	1.00	-0.83	-0.87	-0.90	-0.80	-0.76
DOC	-0.83	1.00	0.73	0.79	0.78	0.91
u-MeHg	-0.90	0.79	0.88	1.00	0.70	0.77
All Stations						
DO Conc	1.00	-0.60	-0.71	-0.66	-0.61	-0.63
DOC	-0.60	1.00	0.59	0.69	0.79	0.83
u-MeHg	-0.66	0.69	0.82	1.00	0.60	0.71

Notes
1. Values in gray are not significantly significant
2. Values shaded in yellow have >50% explained through correlation.

Table 6. Comparing Wetland Management Effects on Water Quality Characteristics

Table presents changes in water quality correlated with an action, treatment or marsh characteristic.

			Water Quality Characteristic [1,3,4]									
Treatment [4]	Flag [2]	Value [2]	***DOC***	SUVA	MeHg (f)	***MeHg (u)***	SSC	***DO Conc***	NTU	pH	SC	***Temp***
WCS	No	0	***-0.180***	-0.018	-0.055	***-0.142***	-0.093	***0.297***	0.037	0.070	0.019	***0.327***
	Yes	1	***N=270***	N=270	N=203	***N=206***	N=111	***N=81***	N=81	N=81	N=80	***N=81***
			p=.003	p=.774	p=.436	***p=.043***	p=.330	***p=.007***	p=.745	p=.533	p=.870	***p=.003***
Soil Description [6]	An	1	0.084	**0.157**	**0.262**	0.069	**-0.230**	0.040	-0.037	0.085	0.015	0.043
	Ta	2	N=270	**N=270**	**N=203**	N=206	**N=111**	N=81	N=81	N=81	N=80	N=81
	Sp	3	p=.170	**p=.010**	**p=.000**	p=.324	**p=.015**	p=.723	p=.744	p=.452	p=.897	p=.701
Depth	Shallow	1	-0.086	0.032	0.033	0.003	0.075	0.204	0.085	0.159	**0.353**	0.208
	Medium	2	N=240	N=240	N=174	N=175	N=93	N=75	N=75	N=75	**N=74**	N=75
	Deep	3	p=.184	p=.619	p=.667	p=.968	p=.472	p=.079	p=.471	p=.174	**p=.002**	p=.073
In Perimeter ditch	No	0	-0.077	0.037	0.042	0.000	0.049	**0.229**	0.113	0.106	0.185	0.131
	Yes	1	N=270	N=270	N=203	N=206	N=111	**N=81**	N=81	N=81	N=80	N=81
			p=.209	p=.550	p=.552	p=.996	p=.610	**p=.039**	p=.313	p=.346	p=.100	p=.246
In/influenced by marsh channel or swale	No	0	***0.154***	0.038	0.028	***0.139***	**0.195**	***-0.261***	-0.026	-0.082	0.101	***-0.287***
	Yes	1	***N=270***	N=270	N=203	***N=206***	**N=111**	***N=81***	N=81	N=81	N=80	***N=81***
			p=.011	p=.532	p=.689	***p=.046***	**p=.040**	***p=.019***	p=.815	p=.469	p=.371	***p=.009***
In interior Marsh plain	No	0	**0.136**	0.033	0.084	0.078	0.130	-0.132	-0.029	0.037	0.018	-0.133
	Yes	1	**N=270**	N=270	N=203	N=206	N=111	N=81	N=81	N=81	N=80	N=81
			p=.025	p=.586	p=.232	p=.266	p=.175	p=.242	p=.795	p=.743	p=.871	p=.238
Near sewage effluent point	No	0	***-0.146***	**-0.134**	**-0.202**	***-0.190***	0.026	***0.264***	-0.162	0.026	**-0.390**	***0.428***
	Yes	1	***N=270***	**N=270**	**N=203**	***N=206***	N=111	***N=81***	N=81	N=81	**N=80**	***N=81***
			p=.017	**p=.028**	**p=.004**	***p=.006***	p=.785	***p=.017***	p=.149	p=.815	**p=.000**	***p=.000***
Mowed or Disked	No	0	0.102	-0.011	-0.035	0.090	0.157	-0.147	-0.112	-0.002	-0.087	-0.138
	Yes	1	N=270	N=270	N=203	N=206	N=111	N=81	N=81	N=81	N=80	N=81
			p=.093	p=.858	p=.623	p=.199	p=.101	p=.189	p=.322	p=.985	p=.446	p=.220
Chemical Treatment	No	0	-0.008	-0.051	-0.108	0.037	0.155	-0.165	0.075	-0.136	0.127	-0.107
	Yes	1	N=270	N=270	N=203	N=206	N=111	N=81	N=81	N=81	N=80	N=81
			p=.891	p=.402	p=.125	p=.595	p=.105	p=.140	p=.504	p=.225	p=.260	p=.340

Notes

1. Values shown are r values with corresponding N and p values relating water quality characteristic to marsh flag
2. Flags identify different marsh characteristics. A corresponding numeric value is used to identify linear correlations
3. Red bolded values represent values in which correlation is statistically significant ($p<0.05$).
4. Bolded and italicized treatments and water quality characteristics show above average number of significant relationships
5. Highlighted treatment vwater quality characteristics identified as key relationships.
6. An = Silty Clay Loam, Ta = Muck Clay, Sp = Peaty Muck

Table 7. Recorded Drain and Flood Events

Club	Event	Drain Events								Flood Events							
		Start		End		Calculations				Start		End		Calculations			
		Date	Elev Ft-NAVD	Date	Elev Ft-NAVD	Del Elev Ft	Del Vol Ac-Ft	Duration Days	Qave Ft^3/s	Date	Elev Ft-NAVD	Date	Elev Ft-NAVD	Del Elev Ft	Del Vol Ac-Ft	Duration Days	Qave Ft^3/s
123																	
Fall	A									18-Sep-07	2.5	23-Sep-07	4.2	-1.71	-194	4.6	-21
	B	23-Sep-07	4.2	27-Sep-07	2.5	1.76	163	4.4	19	27-Sep-07	2.5	2-Oct-07	4.3	-1.77	-253	5.4	-24
Winter	A	9-Feb-08	4.1	13-Feb-08	1.4	2.74	239	4.4	27	13-Feb-08	1.4	25-Feb-08	4.3	-2.96	-294	11.6	-13
	B	3-Mar-08	4.4	7-Mar-08	1.4	3.00	305	3.8	41	10-Mar-08	1.4	16-Mar-08	3.8	-2.46	-171	5.3	-16
Fall	A									22-Sep-08	1.6	28-Sep-08	4.6	-3.06	-360	6.3	-29
	B	28-Sep-08	4.6	3-Oct-08	2.4	2.22	348	5.2	34	5-Oct-08	2.4	14-Oct-08	4.4	-1.98	-288	9.1	-16
Average						***2.4***	***263.7***	***4.5***	***30.0***					***-2.3***	***-260.0***	***7.0***	***-19.8***
112																	
Fall	A									29-Sep-07	2.6	1-Oct-07	5.3	-2.70	-47	2.6	-9
	B	1-Oct-07	5.3	3-Oct-07	3.7	1.55	42	1.5	15	3-Oct-07	3.7	6-Oct-07	5.2	-1.44	-35	2.2	-8
Winter	A	30-Jan-08	5.9	2-Feb-08	3.8	2.09	104	3.2	16	2-Feb-08	3.8	6-Feb-08	5.4	-1.66	-55	4.2	-7
	B	6-Feb-08	5.4	9-Feb-08	3.4	2.09	58	2.9	10	9-Feb-08	3.4	14-Feb-08	5.4	-2.05	-55	4.9	-6
	C	14-Feb-08	5.4	19-Feb-08	3.3	2.13	55	5.1	5	19-Feb-08	3.3	25-Feb-08	5.9	-2.64	-113	5.8	-10
Fall	A1									1-Oct-08	2.7	4-Oct-08	5.2	-2.45	-42	3.2	-6
	A2									14-Oct-08	5.5	19-Oct-08	6.1	-0.57	-71	5.3	-7
	B	19-Oct-08	6.1	22-Oct-08	4.6	1.44	117	2.7	22	27-Oct-08	4.6	3-Nov-08	5.7	-1.11	-66	7.4	-4
Average						***1.9***	***75.2***	***3.1***	***13.6***					***-1.8***	***-60.5***	***4.5***	***-7.1***

Table 8. Calculated Regression Values for imported and exported loads from the wetlands

	Loads Descriptions		Slope						N	R^2
			Estimate	Std Error	t-value	p-level	Lo. Conf	Up. Conf		
DOC	Slope Units		([mg/m2/tide] / inches water on or off)							
	Import		*468*	*57*	*8.27*	*0.0000*	*350*	*585*	22	0.4726
	Export	112	*306*	*58*	*5.30*	*0.0000*	*186*	*427*	22	0.9411
		123	*826*	*41*	*20.12*	*0.0000*	*740*	*912*		
f=meHg	Slope Units		([ng/m2/tide] / inches water on or off)							
	Import		27	ND	ND	ND	ND	ND	20	0.0884
	Export	112	4	20	0.22	0.8291	-38	47	20	0.6455
		123	*92*	*14*	*6.35*	*0.0000*	*61*	*122*		
u-meHg	Slope Units		([ng/m2/tide] / inches water on or off)							
	Import		48	ND	ND	ND	ND	ND	21	0.1595
	Export	112	31	18	1.72	0.1011	-7	69	21	0.7749
		123	*117*	*13*	*9.10*	*0.0000*	*90*	*143*		

Notes
1 Italicized estimates are significant ($p<0.05$).
2 ND = Not determined

Table 9. Estimating Exports Loads from Wetlands for the Different Water Management Objectives over the fall and winter seasons.

Calculations use the estimated loads from Table 8.

Club	Season	Water Mgmt Objective	Flow Off Per Tide inches	DOC Load mg/m2-tide)
112	Fall	Continuous	0.24	75
		Drain	0.45	139
		Flood	0.39	118
	Winter	Continuous	0.39	120
		Drain	0.35	109
		Flood	0.36	109
123	Fall	Continuous	0.59	489
		Drain	1.35	1117
		Flood	0.49	407
	Winter	Continuous	0.73	601
		Drain	1.35	1114
		Flood	0.19	155

Appendix D. Aquatic Ecology

Strategy for Resolving MeHg and Low Dissolved Oxygen Events in Northern Suisun Marsh

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ABSTRACT

We examined factors affecting fish and invertebrate abundance and distribution within sloughs in Suisun Marsh, focusing especially on the effects of low dissolved oxygen (DO) concentrations. Suisun Marsh, at the geographic center of the San Francisco Estuary, is important habitat for introduced and native fishes, especially for early life history stages. The University of California, Davis, Suisun Marsh Fish Study has systematically monitored the marsh's fish populations since 1980. The purpose of the study has been to determine the environmental factors affecting fish abundance and distribution, especially in relation to water management activities. In 2007 and 2008, extra effort was put into sampling sloughs subject to low DO events. In 2007, beach seine and otter trawl catches were relatively low. High catches of a few introduced species in 2006 and their subsequent decline in numbers in 2007 were the primary determinants of otter and beach seine catch-per-unit effort-values (CPUE) for both years. Most fishes peaked in abundance in the warmer months, mainly due to influxes of young-of-year. Catch of many species plummeted in late summer concurrent with increasing numbers of Black Sea jellyfish (*Maeotias marginata*). Four invertebrates commonly captured in otter trawls declined in abundance from 2007 to 2008. Otter trawl CPUE was the second lowest recorded in the study's history, mainly due to the decline of freshwater non-native species and a lack of young-of-year fish. Conversely, many fishes that declined in otter trawls became more abundant in beach seine catches. Our results overall suggest that our lower trawl catches were the result of higher salinities and poor recruitment of young-of-year fish, plus some movement of fish from channel habitats to shoreline areas. However, we also found that DO affected the biota: lowest numbers of fish were found in sloughs that experienced low DO events on a regular basis, and the fish and invertebrates found in such sloughs were mostly species with high tolerance for low DO. It is worth nothing that recovery times in depleted sloughs can be fairly rapid given the mobility of fishes, depending on reproductive success and behavior of certain species. In the absence of periodic low DO events in smaller sloughs with duck club discharges, the variability in fish abundance and diversity would more resemble those of small sloughs without such discharges. It appears that even events that only occur once every 2-3 years may keep sloughs from recovering their more desirable fishes completely.

INTRODUCTION

Suisun Marsh is a brackish-water marsh bordering the northern edge of Suisun Bay in the San Francisco Estuary; it is the largest contiguous estuarine marsh remaining in the western United States. Most of the marsh area is diked wetlands managed for waterfowl, with the rest of the acreage consisting of tidally influenced sloughs (California Department of Water Resources 2001). The marsh's central location in the San Francisco Estuary makes it an important rearing area for euryhaline freshwater, estuarine, and marine fishes.

The University of California, Davis, initiated the Suisun Marsh Fish Study in 1979 to monitor the abundance and distribution of fishes in relation to each other, to environmental variables, and to water management activities (e.g., water exports, operation of the Suisun Marsh Salinity Control Gates). The study has used two primary methods for sampling fishes: beach seines and otter trawls. Moyle et al. (1986) evaluated the first five years of data collected by the study and found three groups of species that exhibited seasonal trends in abundance, primarily due to recruitment. The structure of the fish community was relatively constant through time; however, total fish abundance declined over the five years. The decline was partly due to strong year-classes early in the study period, which was followed by both extremely high river discharges and drought that resulted in poor recruitment. The authors also found that native fishes tended to be more prevalent in small, shallow sloughs not confined by levees, while introduced species were more prominent in large sloughs.

Meng et al. (1994) incorporated eight more years into their study, which revealed that the fish assemblage structure was less constant over the longer time period than the earlier study indicated. Additionally, introduced fishes had become more common in small, shallow sloughs, possibly as a result of drought and high exports allowing increased salinities in the marsh and depressing reproductive success of native fishes. Both Moyle et al. (1986), and Meng et al. (1994) found a general decline in total fish abundance (particularly in the native fishes) through time. Matern et al. (2002) found results similar to Meng et al. (1994): fish diversity was highest in small sloughs, and native fish abundances continued to decrease.

For much of the duration of the Suisun Marsh Fish Study, low DO events and associated fish kills have been observed coincident with flood-up in autumn (Schroeter and Moyle 2004). These events have been more common and more severe in smaller sloughs with a high density of diversions/outfalls (Schroeter and Moyle 2004, O'Rear et al. 2009). Thus, in 2007 and 2008, UC Davis added five sites within Peytonia, Boynton, Suisun, and Montezuma sloughs to better evaluate the effects on fishes of low DO events caused by the drainage of duck clubs. This appendix reports the results of the 2007-2008 Suisun Marsh low DO study and discusses differences in aquatic ecology in sloughs within the study period and among years.

METHODS

Objectives

The major objective of the low DO study is to examine short-term changes in the sloughs within the low DO study in relation to the greater Suisun Marsh ecosystem. Secondary objectives include (1) enhancing the understanding of the factors determining the abundance, distribution, and community structure of introduced and native fishes; (2) monitoring the effects of water management operations and associated infrastructure (e.g., duck club operations) on marsh fishes; and (3) contributing to the understanding of the life history and ecology of key species in the marsh (O'Rear and Moyle 2008, 2009).

Study Area

Suisun Marsh is a tidally influenced brackish-water marsh covering about 34,000 hectares (California Department of Water Resources 2001). Roughly two-thirds of the marsh area is diked wetlands managed for waterfowl; the remainder consists of sloughs that separate and deliver water to the wetland areas (California Department of Water Resources 2001). The marsh is contiguous with the northern boundary of Suisun Bay and is central to the San Francisco Estuary (Figure 1; O'Rear and Moyle 2008).

There are two major tidal channels in the marsh: Montezuma and Suisun sloughs (Figure 1). Montezuma Slough generally arcs northwest from the confluence of the Sacramento and San Joaquin rivers, then curves southwest and terminates at Grizzly Bay (the major embayment of Suisun Bay). Major tributary sloughs to Montezuma are Denverton and Nurse; Cutoff Slough and Hunters Cut connect Suisun and Montezuma sloughs (Figure 1; O'Rear and Moyle 2008). Suisun Slough begins near Suisun City and trends south until emptying into Grizzly Bay southwest of the mouth of Montezuma Slough. Major tributaries to Suisun Slough, from north to south, are Peytonia, Boynton, Cutoff, Wells, and Goodyear sloughs (Figure 1). First and Second Mallard sloughs are tributary to Cutoff Slough and are part of the Solano Land Trust's Rush Ranch Open Space preserve; Rush Ranch is part of the San Francisco Bay National Estuarine Research Reserve (http://www.nerrs.noaa.gov/SanFrancisco/welcome.html; O'Rear and Moyle 2008).

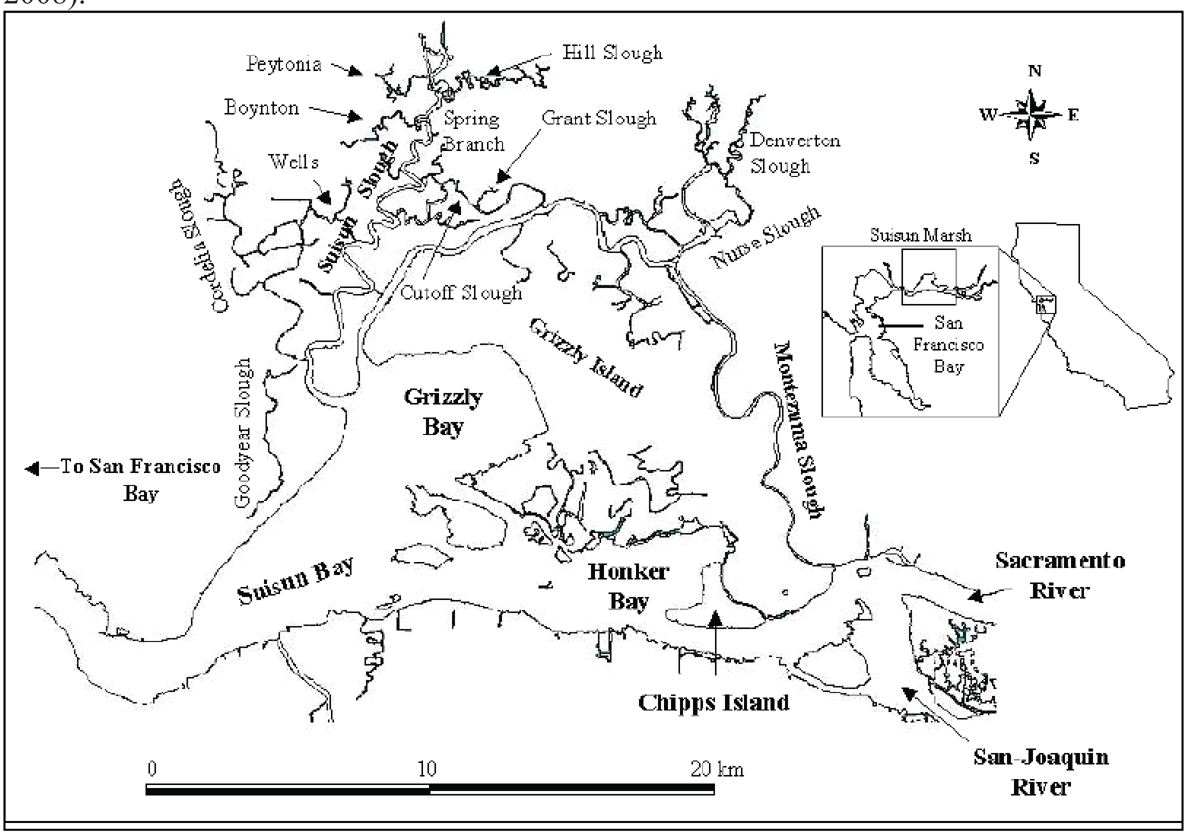

Figure 1. Suisun Marsh.

Suisun and Montezuma sloughs are generally 100-150 m wide, 4-8 m deep, and partially riprapped (Meng et al. 1994). Tributary sloughs are usually 7-10 m wide, 1-4 m deep, and fringed with common reed (*Phragmites communis*) and tules (*Schoenoplectus* spp.). Substrates in all sloughs are generally fine organics, although a few sloughs also have bottoms partially comprised of coarser materials (e.g., Denverton Sloughs).

The amount of fresh water flowing into Suisun Marsh is the major determinant of its salinity. Fresh water enters the marsh primarily from the Sacramento River through Montezuma Slough, although small creeks, particularly on the northwest side of the marsh, also contribute fresh water to the smaller sloughs. As a result, salinities are generally lower in the eastern and northwestern portions of the marsh. Freshwater inflows are highest in winter and spring due to rainfall runoff and snowmelt in the Sacramento and San Joaquin hydrologic regions; consequently, marsh salinities are often lowest in these seasons. Salt water enters the marsh through lower Suisun and Montezuma sloughs from Grizzly Bay via tidal action, although the effect of the tides is primarily on water surface elevation and not salinity throughout much of the year (Matern et al. 2002). During extreme tides, water depths can change as much as 1 m over a tidal cycle, often dewatering more than 50 percent of the smaller sloughs at low tide and overtopping dikes at high tide (O'Rear and Moyle 2008).

A number of water management facilities influence the hydrology and water quality of the marsh. State Water Project and Central Valley Project water export facilities in the southern Delta affect the timing and magnitude of freshwater inflow into Suisun Marsh. The Suisun Marsh Salinity Control Gates, which are located in Montezuma Slough just downstream of the confluence of the Sacramento and San Joaquin rivers, are operated to inhibit saltwater intrusion into the marsh during flood tides, thereby providing fresher water for diked wetlands (California Department of Water Resources 2001; Figure 1). Numerous diversion intakes/outfalls are located throughout the marsh; they are most commonly operated from early autumn to early spring for attracting and providing overwintering habitat for waterfowl. Duck club drainage water is discharged directly into numerous sloughs within the marsh. Goodyear Slough is now connected to Suisun Bay by a channel that was built to depress salinities in the slough for water diverters in the western portion of the marsh (O'Rear and Moyle 2008).

Sampling

Since 1980, monthly juvenile and adult fish sampling has been conducted at standard sites within Suisun Marsh. Prior to 1994, a total of 12 sloughs and 27 sites were sampled. Several of these historic sites were sampled only in 1980 and 1981, with 17 sites being sampled consistently until 1994 (see O'Rear and Moyle 2008). From 1994 to the present, 21 sites in nine sloughs have been regularly sampled (Figure 2). In 2007 and 2008, five additional sites were otter trawled as part of the Suisun low DO project in order to better understand the effects of duck-pond discharge water on the marsh's ecology: one in Peytonia Slough just downstream of the PT2 site; one in Boynton Slough between the BY1 and BY3 sites; one in upper Suisun Slough between the SU1 and SU2 sites; and two in Montezuma Slough immediately downstream of the mouth of Nurse Slough (Figure 2). These sites were trawled from January to March and from September to December. Latitude and longitude coordinates for current, regularly sampled sites were obtained (± 100 m) using a Global Positioning System receiver (adjustments made by Alan Kilgore of the California Department of Fish and Game's Technical Services Branch GIS) and are found in

Schroeter et al. (2006). Latitude and longitude for the additional five sites from the low DO Project were obtained using California San Francisco Bay Map on Terrain Navigator® software from MAP TECH, Inc.

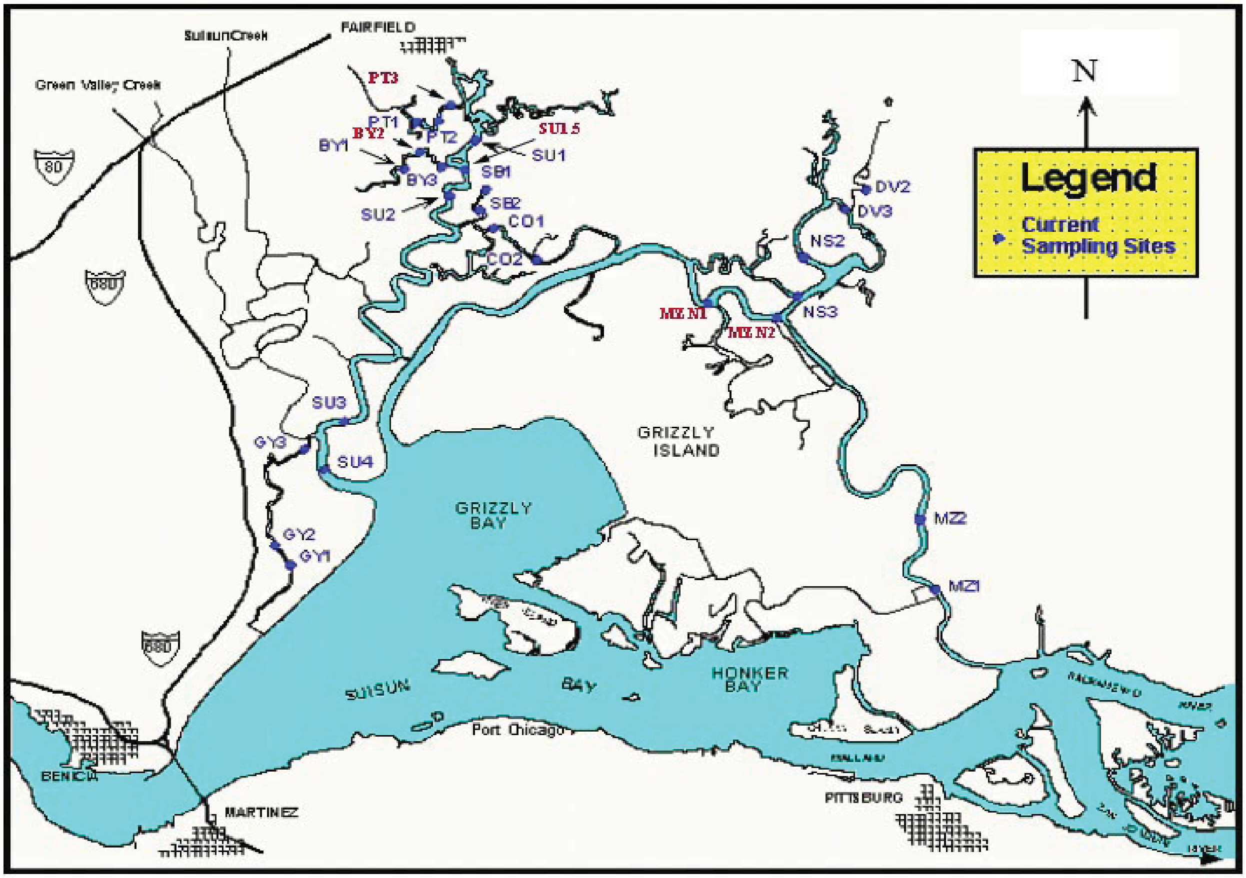

Figure 2. Location of Suisun Marsh sampling sites, with study sites shown in red (from Schroeter et al. 2006)

Trawling was conducted using a four-seam otter trawl with a 1.5 m X 4.3 m opening, a length of 5.3 m, and mesh sizes of 35 mm stretch in the body and 6 mm stretch in the cod end. For each site, temperature (degrees Celsius, °C), salinity (parts per thousand, ppt), and specific conductance (microsiemens, µS) were measured with a Yellow Springs Instrument (YSI) 85 meter; dissolved oxygen parameters (mg/l and % saturation), first measured in 2000, were also recorded (O'Rear and Moyle 2008) with the same instrument. Tidal stage (incoming, high, outgoing, low), water transparency (Secchi depth, cm), and water depths (m) were also recorded.

Contents of each trawl or seine were placed into large containers of water. Fishes were identified, measured to the nearest millimeter standard length (mm SL), and returned to the water. Sensitive native species were processed first and immediately released. Numbers of Siberian prawn (*Exopalaemon modestus*), Black Sea jellyfish (*Maeotias marginata)*, Oriental shrimp (*Palaemon macrodactylus*), California bay shrimp (*Crangon franciscorum*), overbite clam (*Corbula amurensis*), and Asian clam (*Corbicula fluminea*) were also recorded. Crustaceans from the order Mysida were pooled into one category, "mysids," and given an abundance ranking: 1 = 1-3 mysids, 2 = 3-50 mysids, 3 = 51-200 mysids, 4 = 201-500 mysids, and 5 = >500 mysids. The index was necessary because most mysids pass through the trawl, and those that remain in the net are difficult to accurately count (O'Rear and Moyle 2008).

All data collected by the study is available on the Bay Delta and Tributaries website (http://bdat.ca.gov/) or from the authors.

Data analysis

For this report, CPUE values for fishes were calculated as

$$CPUE_{ax} = \frac{number\ of\ \ fish\ in\ a\ in\ period\ x}{number\ of\ \ trawls\ in\ a\ in\ period\ x}$$

where x is a year, a number of years, or a month; and a is a slough. CPUE values for invertebrates were also calculated likewise, with the number of individuals for the invertebrate of interest substituting for "number of fish." Water quality averages were calculated as for CPUE values, with the sum of the measurements of the water quality parameter of interest (e.g., Secchi depth, water temperature) substituting for "number of fish." X2 was calculated following Jassby (1995). Delta outflow was obtained from the California Department of Water Resource's Dayflow website (2009). Results were then graphed and compared.

RESULTS

Abiotic Factors

Delta Outflow.

2007 was considerably drier than 2006, resulting in comparatively low Delta outflow for much of the year. Only in February did outflows increase substantially: once in the early part of the month when a low-pressure system poured rain on Northern California, and at the end of the month, when cold storms dumped snow in the mountains and rain in the valleys. A few storms at the beginning and end of December elevated Delta outflow, although much less than the February storms and for shorter periods.

2008 was a dry year. Above average precipitation in January elevated Delta outflow to its yearly maximum of about 48,000 cfs; storms at the end of January and beginning of February also increased the amount of water leaving the Delta (Figure 3). Late February storms raised Delta outflow into the beginning of March; however, unlike 2006, outflow declined and remained low through the remainder of spring and throughout summer (Figure 3). Delta outflow did not increase substantially again until the first significant autumn storm hit in early November. Rain in the second and third weeks of December also raised outflow, albeit mildly (O'Rear and Moyle 2009).

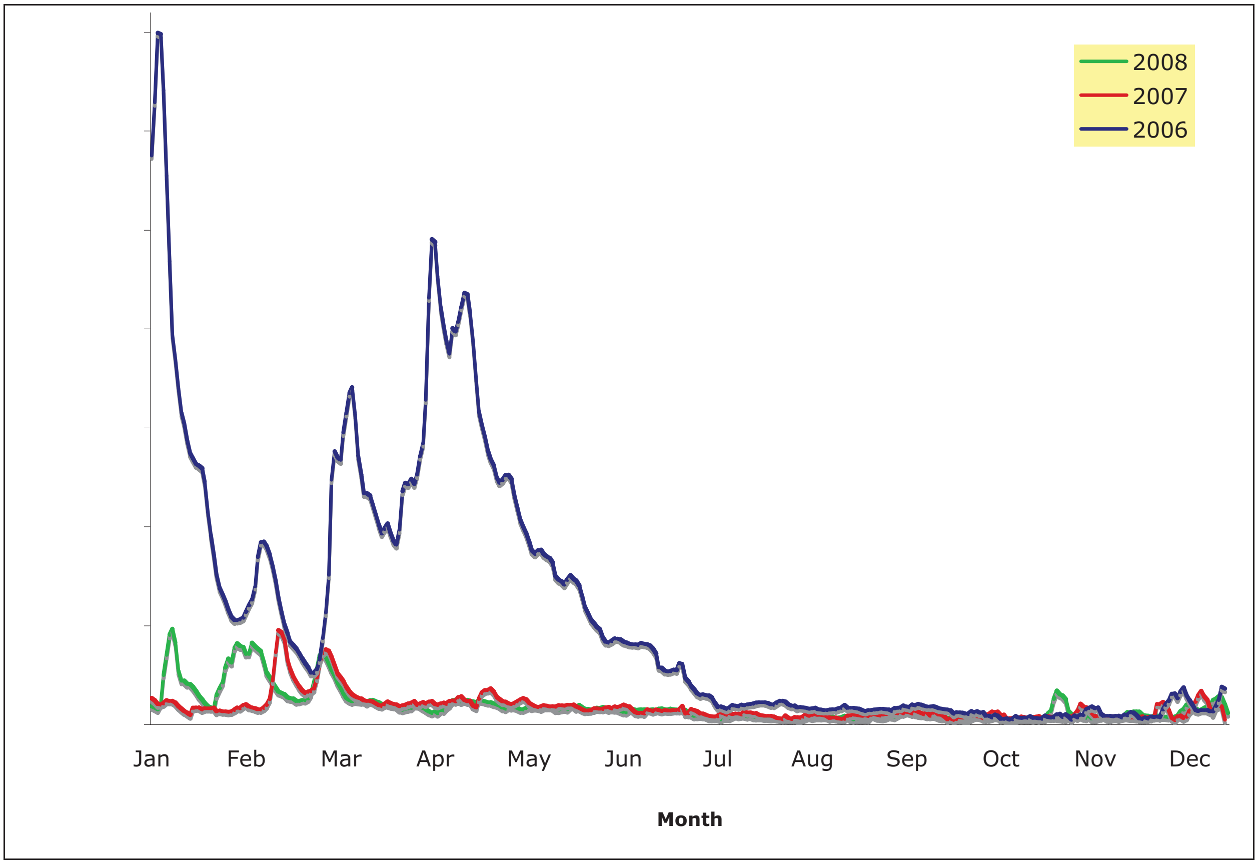

Figure 3. Net Delta outflow 2007-2008.

Salinity

As expected with the dry year, 2007 salinities in Suisun Marsh were generally greater than the 27-year average. However, salinities were lower than expected in December 2007, which probably reflected the effects of the Suisun Marsh Salinity Control Gates (O'Rear and Moyle 2008). Salinities in Suisun Marsh generally increase from east to west and north to south, with the highest salinities consequently found in the southwestern portion of the marsh (i.e., lower Suisun and Goodyear sloughs). This pattern was generally followed within the low DO study sites during 2007 except that the highest salinities were recorded at the additional Montezuma Slough sites in the fall. In general, all sites stayed close to the average until July except for Montezuma Slough, which was lower than average.

Reflecting the low outflow, the average annual salinity for 2008 was the saltiest recorded since 1992. Average monthly salinities in 2008 were considerably higher than that for the 28-year averages for much of spring, all of summer, and early autumn. Within the low DO sites, salinity was consistent with the average until June when they rose above the average in all sloughs in the study. Salinities were highest in Goodyear Slough, exceeding 16 parts per thousand (ppt) in July, August, and September. The lowest salinity (0.3 ppt) was recorded in Montezuma Slough in February, which was also when salinities were geographically most uniform throughout the marsh (Figure 4; O'Rear and Moyle 2008).

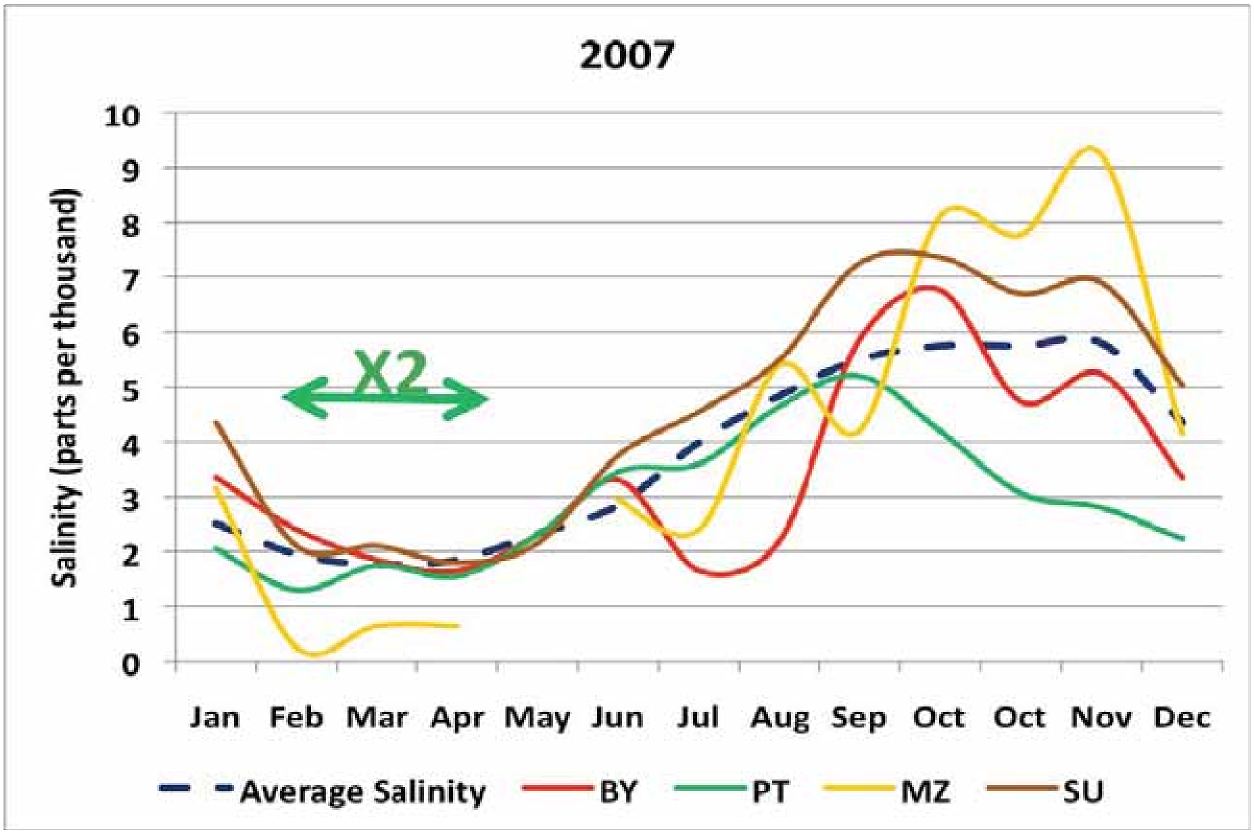

Figure 4. Average salinity over the 28-year study history as compared to average salinity within low DO study sloughs in 2007 (BY = Boynton Slough, PT = Peytonia Slough, MZ = Montezuma Slough, SU = Suisun Slough).

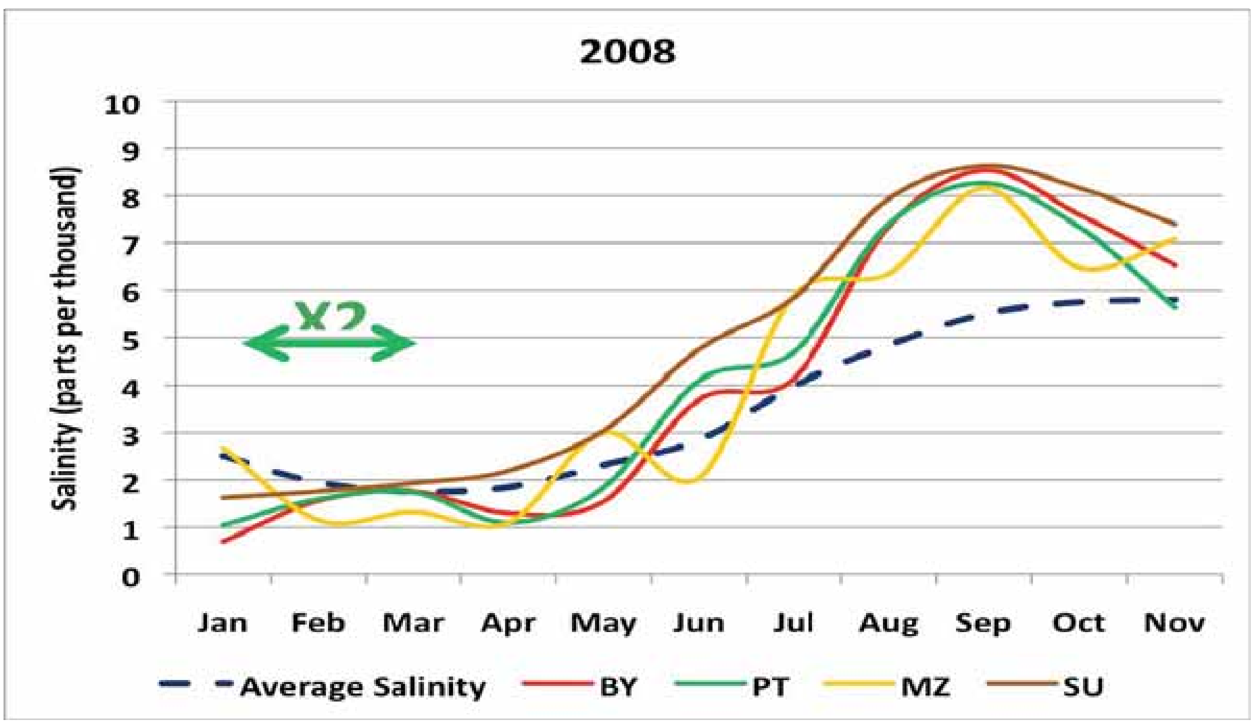

Figure 5. Average salinity over the 28-year history of the study as compared to average salinity within low DO study sloughs in 2008 (codes as in Figure 4).

X2 is another measure of salinity. The location of X2, the distance in kilometers from Golden Gate Bridge (along the thalweg to the near-bed water) of the isohaline of 2 ppt, was historically associated with the productive entrapment zone and high abundances of phytoplankton, macroinvertebrates, and several fishes (Jassby et al. 1995). Consequently, when X2 is located in Suisun Bay, the abundance of fishes in Suisun Marsh is often relatively high. It also follows that the longer X2 is within Suisun Bay, the abundance of fishes in Suisun Marsh should be greater over a longer time span. In 2007, lack of high outflow events and generally low outflow kept X2 upstream of Suisun Bay for much of the year. X2 was located in Suisun Marsh for 23 percent of 2008, with those days occurring in winter and early spring (Figure 4, 5). Unlike in 2006, X2 was in Suisun Marsh before the young of-year of most marsh fishes had hatched or migrated to the marsh. Consequently, few marsh larvae or juveniles were likely to have benefited from conditions often associated with X2 (O'Rear and Moyle 2008).

Temperature

Water temperatures in Suisun Marsh are primarily a function of solar radiation and, to a lesser extent, water volume. Generally, average monthly temperatures follow a pattern typical of temperate regions in the Northern Hemisphere: coldest temperatures occur in winter (December and January) and warmest temperatures occur in summer (July and August). Average monthly temperatures in 2007 strongly mirrored the average regime (Figure 6). Temperature extremes occurred in the months with the average highest and lowest temperatures. The pattern for average monthly water temperatures in 2008 was very similar to that for 2007, as were the temperatures for the low DO sites for both 2007 and 2008. The only noticeable deviation from the usual trend was slightly cooler temperatures in September, which were probably due to the intrusion of cooler, more saline water from San Pablo Bay (O'Rear and Moyle 2008).

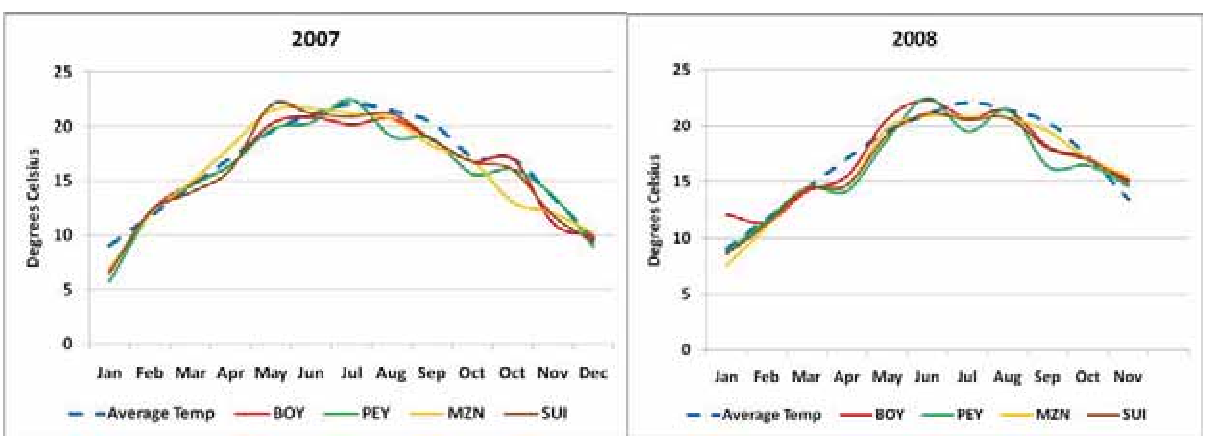

Figure 6. Average temperature over the 28-year history of the study as compared to average temperature within low DO study sloughs in 2007 and 2008.

Water Transparency

The magnitude of freshwater inflow is the primary determinant of water transparency (Secchi depth) in Suisun Marsh. Transparencies in the marsh are usually lowest in spring when river flows are highest; conversely, transparency generally reaches a maximum in October when river flows are at their annual minimum. Although average transparencies in 2007 were slightly higher in the low DO study sites for most months due to the dry year, the pattern was somewhat different in that most sites had lower transparency during the fall and Montezuma was higher than average all year (Figure 7). However, transparency was particularly high in December 2007, which somewhat contradicts the salinity data. Transparency and salinity are both negatively correlated to Delta outflow; thus, closure of the Suisun Marsh Salinity Control Gates may change conditions sufficiently to result in both low salinities and transparencies. In 2008, transparencies within the low DO sites followed the average values closely in early winter; the water became less clear in spring, then clearer during summer. Montezuma Slough was the exception, with very clear water after May (Figure 7). However, it is possible that the low, freshwater Delta outflow captured by the gates in December also had previously lost most of its sediment load, resulting in high transparency concurrent with comparatively low salinity (O'Rear and Moyle 2008).

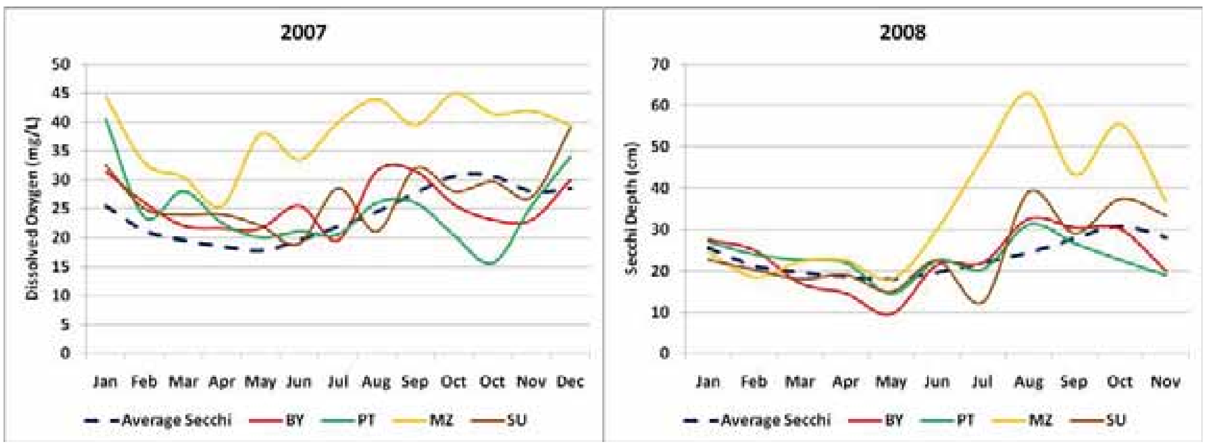

Figure 7. Average Secchi depth over the 28-year history of the study as compared to Secchi depth by month within low DO study sloughs in 2007 and 2008.

Dissolved Oxygen

Dissolved oxygen concentrations in the marsh appear to be substantially affected by duck club operations. Generally, hypoxic water is discharged into sloughs from duck ponds during autumn, lowering oxygen concentrations in the sloughs (Schroeter and Moyle 2004). Likewise, draining ponds in spring during leaching cycles by discharging to the sloughs also depresses marsh oxygen concentrations (R. E. Schroeter, unpublished data). Thus, the yearly pattern of marsh oxygen concentrations exhibits sags in spring and autumn (Figure 8). Monthly average oxygen concentrations within the low DO study sites in 2007 varied from the general trend in two major ways: (1) oxygen concentrations were much lower than the average for all years in February and (2) in June it was appreciably higher than that for all years. In 2007, oxygen concentration dipped below 3 mg/l six times, with the majority of those measurements recorded in Peytonia Slough during October (O'Rear and Moyle 2008).

Average monthly oxygen concentrations in 2008 were highest in winter, decreased considerably in spring, rose somewhat at the end of summer, and then declined again in autumn (Figure 8). Average oxygen concentrations were noticeably lower in 2008 during late spring and summer relative to the averages for all years, which was probably due in part to higher-than-average salinities. Duck club operations were probably partly responsible for the low values seen in April and November. In April, the sloughs with the most diversions per river-kilometer (Boynton, Goodyear, and Peytonia; Matern et al. 2002) also had the lowest average oxygen concentrations. In November, Boynton and Peytonia sloughs had the lowest average oxygen concentrations. Finally, the two lowest oxygen concentration values were measured in April and October (2.2 mg/L) in Goodyear Slough.

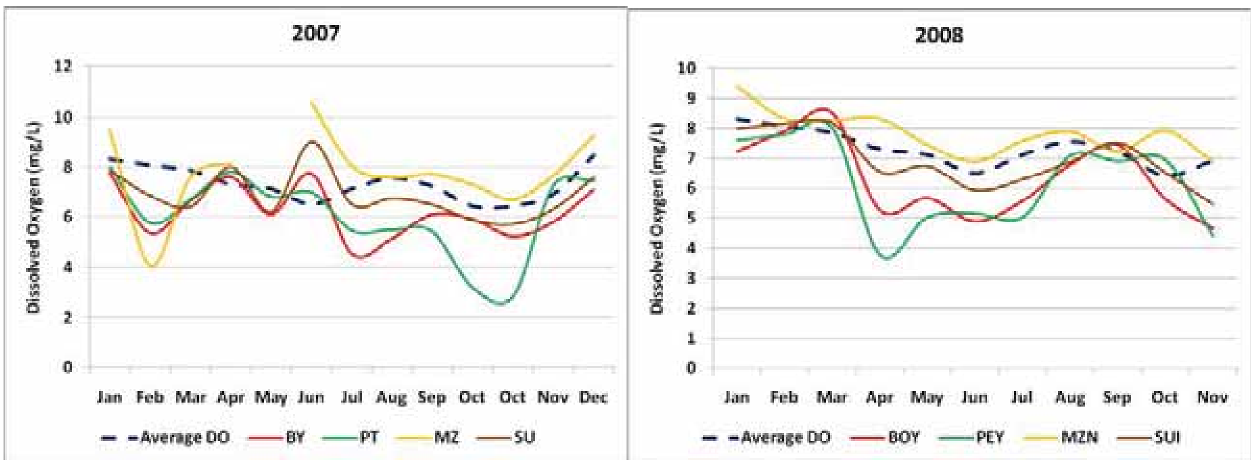

Figure 8. Average dissolved oxygen levels over the 28-year history of the study as compared to oxygen levels by month within low DO study sloughs in 2007 and 2008.

Fishes

Overall fish numbers were exceptionally low during the study period throughout the marsh (Table 1). Two normally abundant fish species, splittail (*Pogonichthys macrolepidotus*) and striped bass (*Morone saxatilis*), whose young are born upriver and migrate into the marsh to rear, were relatively low in abundance as compared to average years. Within the low DO study sloughs, striped bass numbers were low in all sloughs, with splittail numbers being higher in Boynton and Montezuma sloughs but lower in Peytonia and Suisun sloughs. Prickly sculpin (*Cottus asper*), a benthic species, had reduced catches in all study sloughs except for Suisun Slough. In contrast, Pacific staghorn sculpin (*Leptocottus armatus*), another benthic species, was slightly more abundant . Gobies of all species [shimofuri goby (*Tridentiger bifasciatus*), shokihaze goby (*Tridentiger barbatus*), and yellowfin goby (*Acanthogobius flavimanus*)] were all down in numbers within all the sloughs. Catfishes [black bullhead (*Ameiurus melas*)and white catfish (*Ameiurus catus*)] increased in abundance across all sloughs, albeit in very small numbers in Suisun and Montezuma sloughs. Common carp (*Cyprinus carpio*) increased in catch over the length of the study in all sloughs except for Peytonia, where it stayed the same. Threespine stickleback (*Gasterosteus aculeatus*) and tule perch (*Hysterocarpus traski*), both native species, declined in all sloughs except for Montezuma, where tule perch were slightly more abundant during the study. Other fishes caught in the marsh are not mentioned here because they are generally uncommon and are not caught in every year.

Invertebrates

In all sloughs within the study area, both overbite and Asian clams were more abundant than the average catch in the marsh (Table 2). California bay shrimp were low in catch in all low DO study sloughs as compared to the marsh average (Table 2). Siberian prawn were low in Boynton and Peytonia sloughs and slightly higher in Montezuma and Suisun sloughs (Table 2). Oriental shrimp catch was low in all sloughs within the study but very dramatically so within Boynton and Peytonia sloughs. The mysid shrimp index was down for all sloughs within the study. In all sloughs within the low DO study, Black Sea jellyfish increased in numbers.

Table 1. Catch per trawl average for years indicated

Site	BY	BY	MZ	MZ	PEY	PEY	SU	SU
Fish Species Ye	**99-08**	**07-08**	**99-08**	**07-08**	**99-08**	**07-08**	**99-08**	**07-08**
American shad *Alosa sapidissima* ASH	0.07	0.03	0.12	0.06	0.04	0.02	0.08	0.05
black bullhead *Ameiurus melas* BLB	0.88	2.31	0.03	0.07	1.07	3.27	0.05	0.14
black crappie *Pomoxis nigromaculatus* BC	0.25	0.63	0.00		0.48	0.30	0.00	0.00
bluegill *Lepomis Macrochirus*					0.01			
channel catfish *Ictalurus punctatus* CC	0.00	0.02	0.03	0.03			0.02	0.06
common carp *Cyprinus carpio* CP	1.14	1.41	0.05	0.09	0.68	0.68	0.08	0.09
Chinook salmon *Oncorhynchus tshawytscha* CS	0.00		0.01					
delta smelt *Hypomesus transpacificus* DS			0.06				0.00	
fathead minnow *Pimephales promelas* FHM	0.02	0.05			0.01	0.02		
goldfish *Carassius auratus* GF	0.18	0.15	0.00		0.11	0.03		
golden shiner *Notemigonus crysoleucas*					0.00	0.02		
green sunfish *lepomis cyanellus*					0.01			
hitch *Lavinia exilicauda* HCH	0.01	0.02			0.01	0.02		
inland silversides *Menidia beryllina* ISS	0.03	0.03			0.06	0.10		
longfin smelt *Spirinchus thaleichthys* LFS	0.03		0.36	0.09	0.08		0.34	0.05
mosquito fish *Gambusia affinis*					0.00			
Pacific herring *Clupea harengeus* PH			0.08				0.03	
Pacific lamprey *Lampetra tridentata* PL	0.00		0.00					
rainbow trout Oncorhynchus mykiss RT					0.00			
striped bass *Morone saxatilis* SB	3.18	1.42	3.42	2.51	10.23	3.03	3.85	2.24
prickly sculpin *Cottus asper* SCP	0.39	0.15	0.06	0.10	1.48	0.72	0.13	0.17
starry flounder *Platichthys stellatus* SF	0.03	0.12	0.32	0.91	0.04	0.12	0.15	0.39
shimofuri goby *Tridentiger bifasciatus* SG	1.23	0.42	0.07	0.12	3.03	0.63	2.06	0.18
shokihaze goby *Tridentiger barbatus* SKG	0.02	0.03	0.18	0.25	0.19	0.15	0.80	0.70
Sacramento sucker *Catostomus occidentalis* SKF	0.31	0.32	0.01	0.03	0.78	0.58	0.01	0.03
Sacramento pikeminnow *Ptychocheilus grandis* S	0.01	0.02	0.00					
splittail *Pogonichthys macrolepidotus* ST	1.25	1.86	0.79	1.41	4.55	2.42	0.38	0.71
Pacific staghorn sculpin *Leptocottus armatus* STA	0.12	0.22	0.03	0.10	0.11	0.18	0.10	0.14
threespine stickleback *Gasterosteus aculeatus* ST	0.26	0.08	0.09		0.21	0.05	0.23	0.06
threadfin shad *Dorosoma petenense* TFS	0.06	0.03	0.06	0.07	0.65	0.20	0.06	0.05
tule perch *Hysterocarpus traski* TP	0.25	0.20	0.43	0.90	1.17	1.58	0.06	0.18
wakasagi *Hypomesus nipponensis* WAK					0.00		0.01	
white crappie *Pomoxis annularis* WC			0.02	0.06	0.03	0.13	0.00	0.02
white catfish *Ameiurus catus* WCF	0.55	0.59	1.24	1.24	1.53	1.18	0.85	1.21
white sturgeon *Acipenser transmontanus* WS			0.03	0.06			0.09	0.20
yellowfin goby *Acanthogobius flavimanus* YFG	1.69	0.24	0.84	0.71	2.08	0.70	3.17	0.85

Table 2. Catch per trawl average for years indicated

	Site	BY	BY	MZ	MZ	PEY	PEY	SU	SU
Invertebrate Species	**Year**	**99-08**	**07-08**	**99-08**	**07-08**	**99-08**	**07-08**	**99-08**	**07-08**
Asian clam (*Corbicula fluminea*) CORBICULA		0.31	0.98	1.22	3.78	0.60	1.75	0.20	0.56
overbite clam (*Corbula amurensis*) CORBULA		0.15	0.32	0.60	1.93	0.01	0.03	7.21	53.16
CA bay shrimp (*Crangon franciscorum*) CRANGON		4.23	3.08	9.16	8.44	7.71	3.83	19.24	12.97
Chinese mitten crab (*Eriocheir sinensis*) ERIOCHR		0.07		0.03		0.21		0.17	
Siberian prawn (*Exopalaemon modestus*) EXOPAL		30.89	17.44	5.26	9.53	33.63	27.82	27.11	39.64
Harris mud crab (*Rhithropanopeus harrisii*) HARRISMC				0.01	0.04	0.01	0.03		
Black Sea jellyfish (*Maeotias marginata*) MAEOTIAS		18.32	36.71	10.86	17.71	15.19	21.68	30.36	43.15
shrimp from family Mysidae MYSIDS		0.99	0.42	0.55	0.26	1.02	0.45	1.35	0.65
Oriental shrimp (*Palaemon macrodactylus*) PALAEMON		4.64	0.20	0.25	0.09	4.29	0.08	0.12	0.11

DISCUSSION

Study sites

In 2007 and 2008, overall catches of fishes and invertebrates were down both in Suisun Marsh overall and within the low DO study sites. Much of the drop in the fish catch can be attributed to low recruitment of juvenile fishes, which is a function of low fresh water inflow and higher salinity, factors affecting the entire marsh (O'Rear and Moyle 2010, Matern et al. 2002, Meng et al. 1994). Catches of some invertebrates also decreased with these conditions (Siberian prawn), while some increased (overbite clam and Black Sea jellyfish). Many of the species that had reduced catches throughout the marsh exhibited their lowest numbers within Boynton and Peytonia sloughs, while fishes tolerant of low DO levels had higher catches in these two sloughs. In general, fish and invertebrates that were most tolerant of low DO levels were most likely to be found in the sloughs with the lowest DO values (Box 1).

Comparisons with rest of Suisun Marsh

The composition of fish assemblages in Suisun Marsh change from month to month and from year to year as fish move in and out, as reproductive success of different species varies, and as abiotic factors such as freshwater inflow, salinity, and temperature change (O'Rear and Moyle 2008, 2009). Despite this variability, there is a core of species that are typically found in the marsh all year around and respond to local conditions such as low dissolved oxygen levels created by duck club outflows. The immediate effect of these low DO events is to eliminate the community of fish and invertebrates in the sloughs affected (Schroeter and Moyle 2004; O'Rear et al. 2009). While organisms gradually return to the depleted sloughs, there are longer-term effects, especially in Peytonia and Boynton sloughs. Here are some basic observations from the UC Davis fish sampling program to show this (Figures 9-14):

- Fishes that cannot tolerate low DO made up a smaller proportion of the community during fall and winter in Peytonia and Boynton sloughs (e.g., tule perch were virtually absent in 2009, but they were still common in upper Suisun Slough, which had higher DO levels).

- In Peytonia and Boynton sloughs, lowest catches are usually in fall months (Oct-Dec), while in other sloughs (e.g., Suisun Slough) lowest numbers are usually in late winter or spring.
- While catches drop in all sloughs when the water gets cold, they drop more in smaller sloughs with multiple duck club outfalls. In 2008, for example, Denverton Slough, lower Suisun Slough, and First Mallard Slough, which have few or no outfalls, contained a diverse assemblage of fish in autumn and winter, including species that require higher (>5 mg/l) DO levels [e.g., adult striped bass (Coutant 1985, Tupper and Able 2000, Costantini et al. 2008), longfin smelt]. In contrast, Peytonia and Boynton sloughs at the same time had smaller numbers of fish, most of which were low-DO-tolerant species (e.g., black bullhead, white catfish, common carp; O'Rear and Moyle 2009).
- In 2009, tule perch, a species sensitive to low DO levels (Cech et al. 1990), were present in fair numbers in all sloughs during flood-up except in Peytonia, Boynton, and upper Goodyear Slough (which also has low DO issues).
- The fish assemblage of upper Goodyear was affected by low DO in October 2009 when all the fish were killed (O'Rear et al. 2009).

Box 1. Low dissolved oxygen tolerances of Suisun Marsh fishes and macroinvertebrates.

The list below is based on Moyle (2002) and observations in the marsh. For some species, laboratory tolerances may be higher than observed in the marsh. There are also strong interactions among DO, salinity, and temperature which may affect apparent low DO tolerance. Thus, assignments of fish to places on the list should be regarded as hypotheses as much as fact.

Definitions:
1. Specialists. Species that can spend extended periods of time (< 2 hrs) in water with dissolved oxygen levels < 2 mg/l. They often have alternative mechanisms for obtaining oxygen.
2. Tolerant species. Species that regularly occur in water with dissolved oxygen levels of 2-5 mg/l. Such water may not be optimal but is mostly not lethal (but depends on temperature).
3. Non-tolerant species. Species that are rarely found in water that has dissolved oxygen levels less than 5-7 mg/l; they actively avoid or die in water much below saturation levels. For many species this means the water is fairly cold as well (<20°F). Such species actively avoid water with lower D.O. levels.

Species below are listed in approximate order of tolerance to low dissolved oxygen levels under conditions found in Suisun Marsh

Specialists
- Western mosquitofish
- Black Sea jellyfish
- Black bullhead
- Common carp
- White catfish
- Goldfish
- Sacramento splittail

Tolerant species
- Threespine stickleback
- Prickly sculpin
- Shimofuri goby
- Mississippi silverside
- California bay shrimp
- Sacramento sucker
- Yellowfin goby
- Juvenile striped bass
- Threadfin shad
- Adult tule perch
- Black crappie
- Siberian prawn
- Calanoid copepods
- Opposum shrimp
- White sturgeon

Non-tolerant species
- Adult striped bass
- Staghorn sculpin
- Juvenile tule perch
- American shad
- Cladocera
- Delta smelt
- Longfin smelt
- Steelhead
- Chinook salmon
- Northern anchovy
- Pacific herring

Our results overall suggest that our lower trawl catches were the result of a more saline environment and poor recruitment of young-of-year fish, plus some movement of fish from channel habitats to shoreline areas. However, lowest numbers of fish were found in sloughs that experienced low DO events, and the fish and invertebrates found in such sloughs were mostly species with high tolerances for low DO. It is worth nothing that recovery times in depleted sloughs can be fairly rapid given the mobility of fishes and the reproductive success of the non-affected populations. In the absence of periodic low DO events in the smaller sloughs with duck club discharges, the variability in fish abundance and diversity would more resemble those of small sloughs without such discharges. It appears that even events that only occur once every 2-3 years may keep sloughs from recovering their more desirable fishes such as striped bass completely.

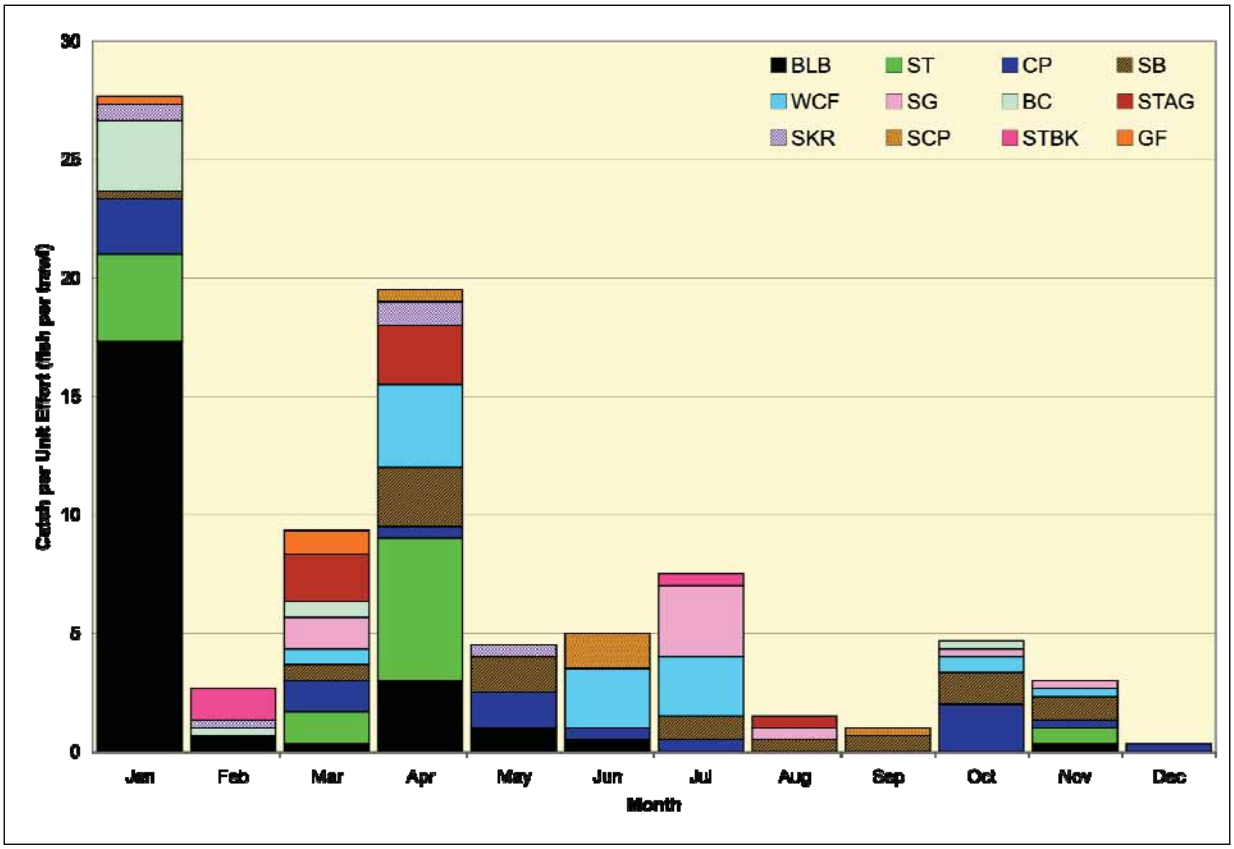

Figure 9. Mean CPUE in UC Davis otter trawls in Boynton Slough by month in 2008. Only most common fish are shown (combined make up 95% of the catch). BLB, black bullhead; ST, splittail; CP, common carp; SB, striped bass; WCF, white catfish; SG, shimofuri goby; BC, black crappie; STAG, staghorn sculpin; SKR, Sacramento sucker; SCP, prickly sculpin; STBK, threespine stickleback; GF, goldfish.

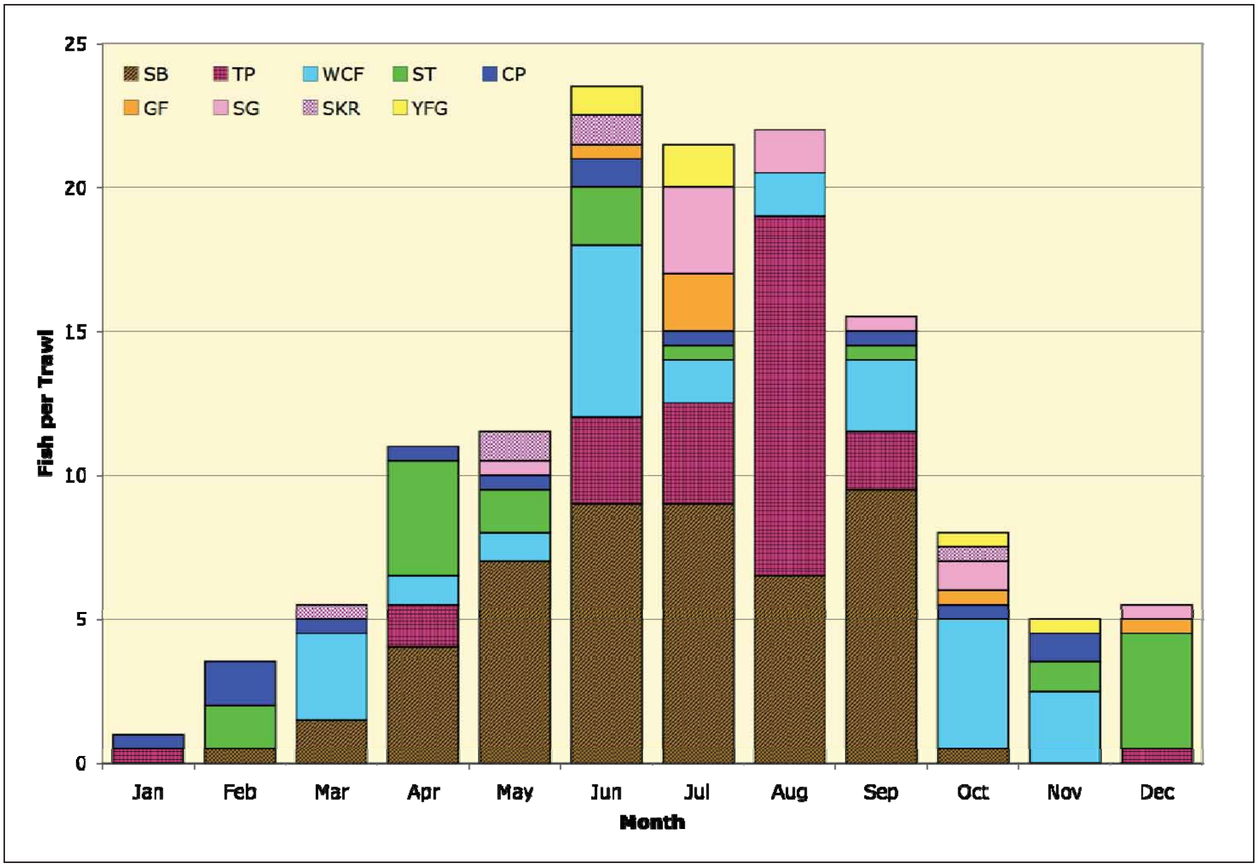

Figure 10. Mean CPUE in UC Davis otter trawls in Boynton Slough by month in 2009. Only most common fish are shown (combined make up 95% of the catch). Acronyms as in Figure 9 except TP, tule perch; and YFG, yellowfin goby.

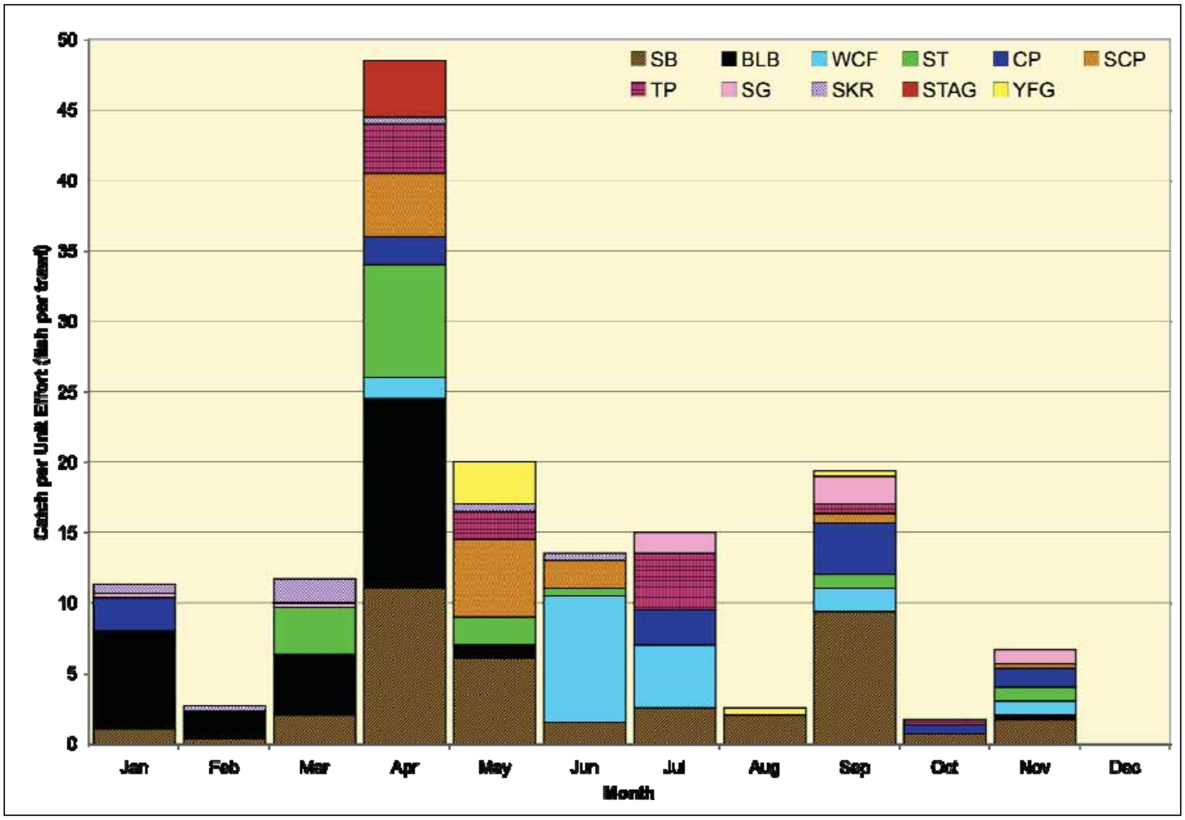

Figure 11. Mean CPUE in UC Davis otter trawls in Peytonia Slough by month in 2008. Only most common fish are shown (combined make up 95% of the catch). Acronyms as in Figure 9 and 10.

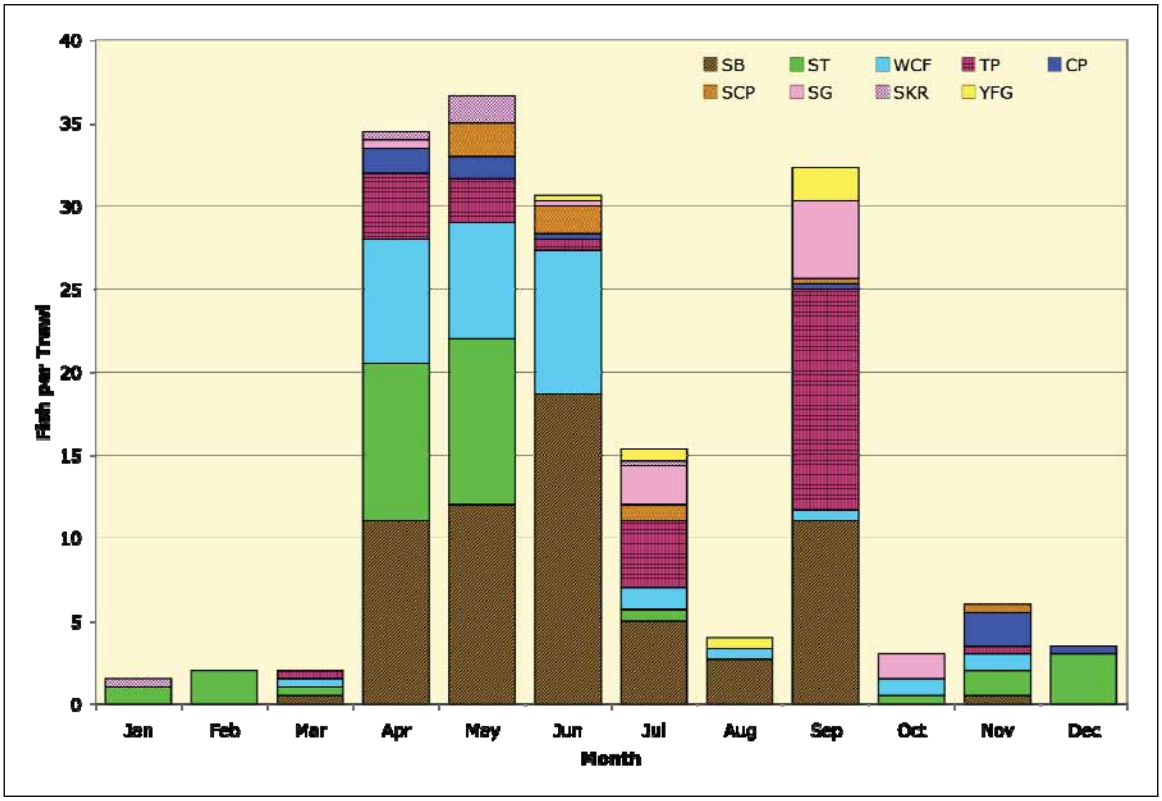

Figure 12. Mean CPUE in UC Davis otter trawls in Peytonia Slough by month in 2009. Only most common fish are shown (combined make up 95% of the catch). Acronyms as in Figure 9 and 10.

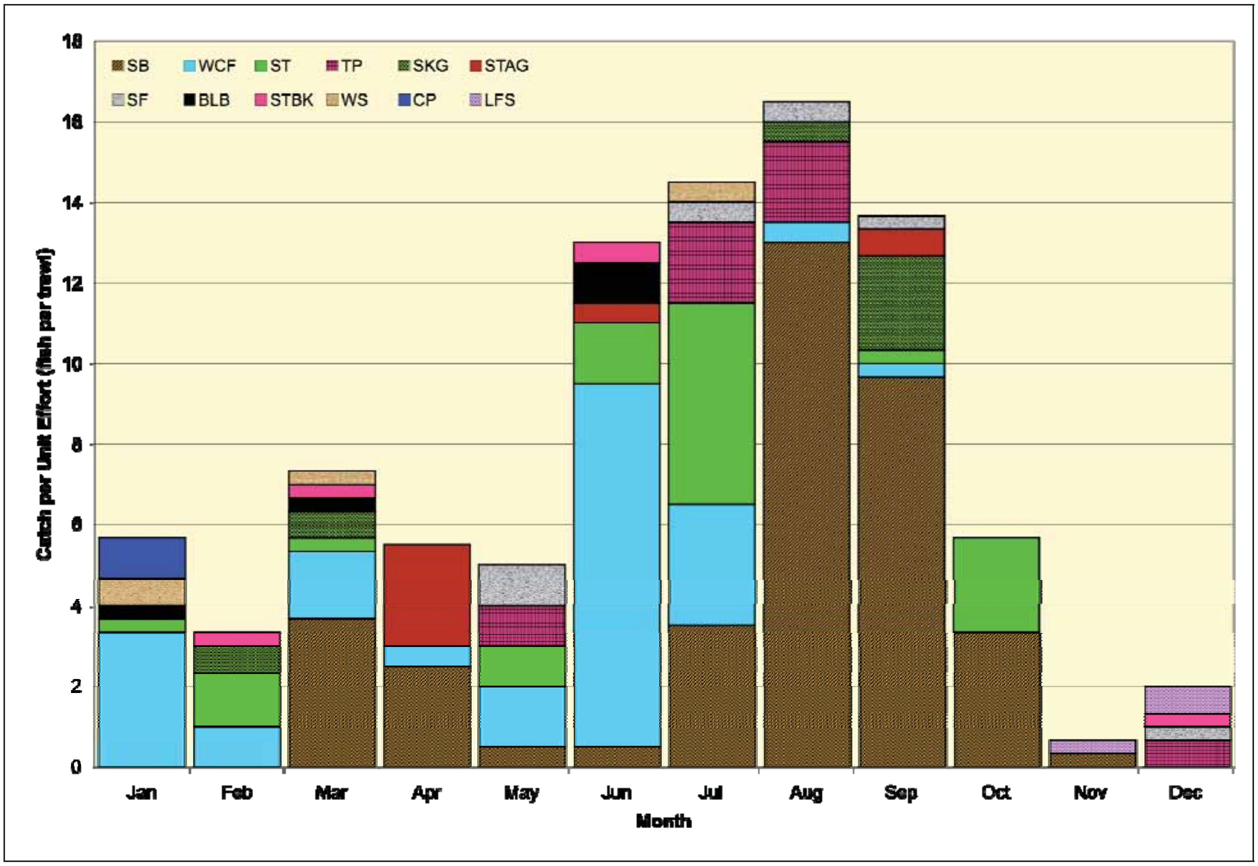

Figure 13. Mean CPUE in UC Davis otter trawls in upper Suisun Slough by month in 2008. Only most common fish are shown (combined make up 95% of the catch). Acronyms as in Figure 9 and 10 except for WS, white sturgeon; SKG, shokihaze goby.

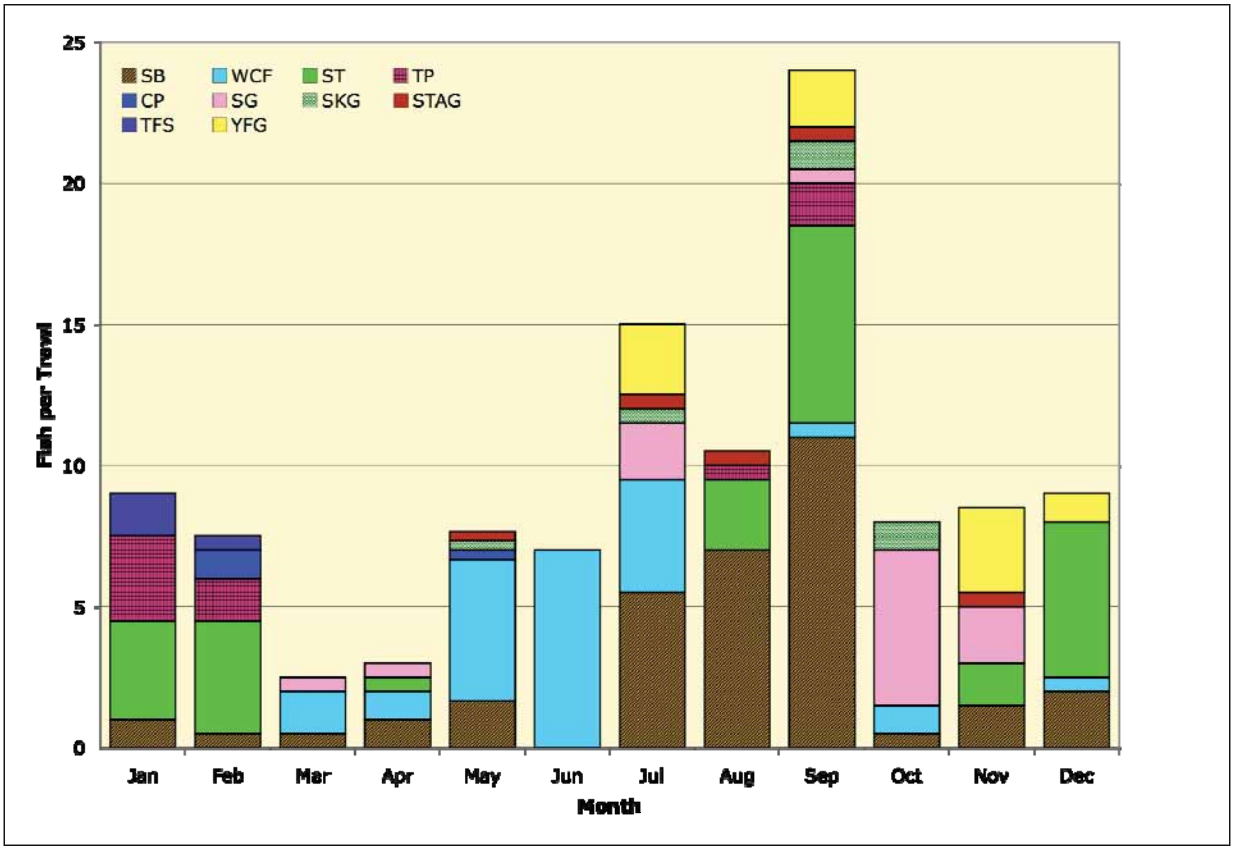

Figure 14. Mean CPUE in UC Davis otter trawls in upper Suisun Slough by month in 2009. Only most common fish are shown (combined make up 95% of the catch). Acronyms as in Figure 9, 10, and 13.

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Strategy for Resolving MeHg and Low Dissolved Oxygen Events in Northern Suisun Marsh

(SWRCB AGREEMENT # 06-283-552-0)
Association of Bay Area Governments

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Chapter 6

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Appendix E

Introduction

The San Francisco Estuary is the largest estuary on the west coast. It is a complex water system involving watersheds that drain over fifty percent of the land in California. The estuary is managed for multiple uses including drinking water, flood control, agriculture, sport fishing, and water fowl hunting. There are over one thousand miles of waterways and multiple habitat types within the estuary. This includes wetlands and marshes which are very important habitats for fish, birds, and wildlife.

Suisun Marsh is located within the San Francisco Estuary downstream from the Sacramento-San Joaquin River Delta and upstream from the Central San Francisco Bay. With about 30,000 acres of sloughs and small bays, about 52,000 acres of managed wetlands, and about 6,300 acres of unmanaged tidal marsh, Suisun Marsh is the largest contiguous brackish water wetland in California. It is also an important wetland on the Pacific Flyway, providing food and habitat for migratory birds.

In addition to providing excellent habitat for wildlife, wetlands create the ideal biogeochemical conditions for increasing the toxicity of mercury (Hg); in the presence of inorganic Hg wetland habitat sets up the ideal conditions for the conversion of Hg to its more toxic organic form mono-methylmercury (MeHg) (Hurley et al., 1995; Rudd, 1995; St. Louis et al., 1994; St. Louis et al., 1996). Many Hg researchers have expressed their concern that marsh restoration efforts and certain management practices could lead to (1) increased MeHg concentrations in fish and birds which reside in the marsh and (2) increase the total amount of MeHg moving through the estuary.

Mercury is an issue in the estuary as a result of historic gold mining operations which utilized Hg in the gold recovery process. Currently there are fish advisories for limiting the amount of fish consumed by anglers in the estuary to protect human health (Office of Environmental Health Hazard Assessment, 2009). Additionally, the concentrations of MeHg in some wetlands exceed 1 ng L^{-1} in water which are 10-20 times greater than those proposed to protect fish and wildlife.

In other areas wetlands have been identified as important sources of MeHg. For example, in the experimental lakes area of Ontario, Canada it was shown that watersheds with wetlands contributed far more MeHg than watersheds with lakes (stratified and non-stratified) and riparian habitats (St. Louis et al., 1994). In other areas in the US and Canada these results were confirmed (Branfireun et al., 1996; Driscoll et al., 1998). Furthermore, it was expected that seasonal wetlands in Suisun marsh would be high producers of MeHg since others have found that wetlands that were allowed to dry produce high concentrations of MeHg when rewetted (Hecky et al., 1991; Rudd, 1995).

There has been little published on MeHg concentrations and loads from wetlands in Suisun Marsh. At the time of this writing we are unaware of existing data which addresses Hg concentrations in relevant bird species in Suisun Marsh. We identify this as a data gap which should be addressed in future work conducted in the marsh. There has been comprehensive monitoring for Hg in silversides in Suisun marsh. Total mercury (Hgt) concentrations in silversides collected from sites within Suisun Bay and Suisun Marsh were highly variable both temporally and spatially (Slotten, 2009). Fish collected 2005 through 2007 from Suisun Bay had whole body Hgt concentrations (wet weight) ranging from 34 to 48 ng g^{-1} (Darell Slotton, unpublished data). Concentrations of Hgt in silversides collected from Suisun Slough were elevated (43 to 96 ng g-1, 2005-2007), compared to fish collected from Suisun Bay (Darell Slotton, unpublished data).

Suisun Marsh MeHg water concentrations were measured at various locations in the sloughs over a period of ~one year starting October, 2005. At Boynton, Peytonia, and Suisun Sloughs MeHg concentrations were seasonally variable ranging from the detection level (0.02 ng L^{-1}) to over 3 ng L^{-1} (Robert Schroeter, unpublished data). Concentrations of MeHg were higher in the fall and winter than during summer months. Coinciding with the elevated MeHg concentrations were declines in oxygen concentrations in the upper sloughs (Robert Schroeter, unpublished data). Seasonal marshes may be identified as a source of MeHg to the sloughs causing the increase in concentrations.

Methylmercury concentrations and loads were measured at three seasonal marsh locations on Grizzly Island October, 2006 to February, 2007 (Heim et al., 2010) The highest MeHg concentrations (1-3 ng L^{-1}) on the managed wetlands were observed during fall and concentrations were always higher in water moving off of the wetlands when compared to source water. Loads of MeHg were estimated for two managed wetland ponds in Grizzly Island. Pond 17 had a load of 0.001 g MeHg day^{-1} and the drainage location was 0.068 g MeHg day^{-1} (Heim et al., 2010). On a per meter squared per year basis the MeHg flux measurements at Grizzly Island are equivalent to some of the highest MeHg flux measurements measured at other wetland or upland areas studied in other states and countries (Driscoll et al., 1998; Heim et al., 2010).

The goal of this project is to answer the following question: to what extent can practical and implementable modifications to water and/or vegetation management practices contribute to reducing the occurrence of elevated MeHg discharge events associated primarily with fall flood-up practices on Suisun Marsh managed wetlands? Specific objectives include working with Suisun Marsh managed wetland managers to implement management practice modifications that would address these water quality concerns, to gather the necessary data to evaluate the effectiveness of these management practice changes, and to produce Best Management Practices that will be distributed amongst the managed wetlands operators throughout Suisun Marsh, via the Suisun Resource Conservation District (SRCD).

Methods

Soil collections

Soil samples were collected September 10, 2007 from the following managed wetlands: Club 112, Club 123, Club 525, Club 529, and Club 530 (Figure 1 & 2). Samples were collected for Hgt and MeHg analysis using techniques shown to be clean for trace metals (Heim et al., 2007). Surficial soil samples were collected using a scoop to remove and transfer the topmost 5 cm to a clean plastic bag. At two central managed wetlands samples were also collected from depth (5 – 10 cm). Samples were kept on ice during transport to the laboratory.

Water collections

Water samples were collected for MeHg and suspended sediment concentration (SSC, first year only) analysis at the edge and interior of the managed wetlands (Figures 1 & 2). The timing of the collections coincided with the seasonal flood up of the wetlands. Samples were collected using ultra clean sampling techniques (Gill and Fitzgerald, 1985; Heim et al., 2009). For the 07-2008 field event the first samples were collected September 21, 2007 and the last samples were collected March 3, 2008. Samples were collected from all five managed wetlands but with greater spatial and temporal resolution at Clubs 112 and 123. Additionally, a limited number of samples were collected from Montezuma Slough. For the 08-2009 field event samples were collected from Clubs 112 and 123 September 22 through November 19, 2008.

Laboratory experiments

Experiment 1. Controlled experiments were conducted to investigate the relationships between vegetation, dissolved oxygen, and MeHg. Experiments were conducted in a temperature controlled environment (24 ºC). Soil (238 grams) collected from Club 123 and sieved to homogenize was added into 4 L widemouth glass jars. The following treatments were set up in triplicate: (1) prewet soil plus 9 grams of swamp timothy (cut up to homogenize), (2) prewet soil only, (3) soil plus 9 grams of swamp timothy, (4) soil only. Preflooded treatments were started on 10/21/08. Three liters of water were added to the microcosms and the water was removed by pump. The jars were reflooded 6 days later on 10/27/08. Non preflooded treatments were started on 10/27/08 as well by adding 3 L of water to the jars. Microcosms were then allowed to equilibrate for 24 hours before sampling began. Samples were then collected daily from 10/28-10/31, every three days from 11/3-11/6, and again on 11/12, and 11/18 for a total of 21 days excluding the 6 days of preflooding and 1 day of equilibration.

Experiment 2. In this second experiment further investigations into the relationships between oxygen, vegetation, and MeHg were conducted by varying the amounts of soil and vegetation and measuring oxygen and MeHg after twenty-one days. Experiments were conducted in a temperature controlled environment (24 ºC). Microcosms were set up using the same wide mouth glass jars as described above with the addition of treatments and 3 liters of purged tapwater shown to be clean for MeHg. The soil was collected from Club 123 and homogenized identical to the first experiment. Also, swamp timothy was used as the added plant material and was added in the dried form after cutting and homogenizing. The treatments were as follows: 1) soil additions were 75, 150, and 240 grams; 2) vegetation additions were 0, 1, 1.5, and 2 grams. A set of treatments were incubated both with and without air additions. In addition, treatments containing 240 grams of sediment and 4 and 8 grams of vegetation were incubated under aerating and non-aerated conditions. All experiments were conducted in triplicate.

Analysis

Hg_T soil analysis. Soil samples were digested by adding 4.0 mL of concentrated HCl to 1.0 g of wet sediment and swirling. Next, 1.0 mL of concentrated HNO_3 was added, swirled, and samples were loosely capped and digested in a fume hood at room temperature overnight. After complete digestion, samples were diluted up to 40 ± 0.5 mL with high purity deionized water (DI, 18 megaohm), capped tightly, shaken vigorously, and allowed to settle until the supernatant was clear. Hg_T was measured by aqueous-phase reduction with stannous chloride solution followed by atomic absorbance detection using an automated PerkinElmer Flow Injection Mercury System (FIMS-100) with the software application AA WinLab (Heim, 2003).

Precision, as indicated by the relative percent difference (RPD) of duplicate measurements averaged 11.4 % for Hg_T in solids (n = 2 pairs). Accuracy, as determined by recoveries of spiked samples and the certified reference material (NIST 1944, 3.4 µg Hg g^{-1} dw sediment), averaged 91.2 % (n = 4) and 101.6 (n = 2) respectively. The method detection limit (MDL), defined as three times the standard deviation of nine determinations of sand, known to be low in Hg and spiked with 60 ng Hg g^{-1} dw sediment, was 4.0 ng Hg g^{-1} dw sediment.

MeHg soil analysis. Soil samples for MMHg analysis were processed by the KBr and CH_2Cl_2 extraction procedure described by (Bloom, 1997). Briefly, 0.5-1.0 g of wet sediment was digested with acidic KBr solution and extracted into 10 mL of CH_2Cl_2 in a 35 mL Teflon® centrifuge tube. A 2.0 mL aliquout of CH_2Cl_2 was then back extracted into DI water by purging out CH_2Cl_2 with high-purity nitrogen gas. Extracts were analyzed for MMHg by aqueous-phase ethylation, trapping on a carbotrap® column, gas chromatography separation, thermal decomposition to elemental Hg, and detection by cold vapor atomic fluorescence spectroscopy (Liang et al., 1994).

Analytical recovery was checked with the certified reference material NIST 1944 (3.4 µg Hg g^{-1} dw sediment, MeHg average of measurements = 4.66 ng MeHg g^{-1} dw sediment). The analytical recovery was 95.2 % (n = 1). The MDL defined as three times the standard deviation of nine determinations of low MMHg content sand, spiked with 0.06 ng MMHg g^{-1} dw sediment, was 0.012 ng MMHg g^{-1} dw sediment. Precision (RPD of duplicate measurements), was 2.9 % for MMHg in solids (n = 1 pair). Accuracy (spike recoveries) averaged 81.3% (n = 2).

MeHg aqueous analysis. Samples were analyzed using a distillation and aqueous phase ethylation method with cold vapor atomic fluorescence spectrometry (CVAFS) detection (Bloom, 1989; Liang et al., 1994). Prior to analysis, 45 to 80 mL aliquots were distilled to minimize recovery artifacts associated with the sample matrix. Distilled samples were then analyzed as described above for extracted sediment samples.

The method detection limits for MeHg determinations was 0.020 ng L^{-1} as determined by replicate measurements of a low level water sample. Analytical recovery was checked by running the certified reference material, DORM-2 (dog fish muscle, 4,470 ± 320 MMHg ng g_{-1} dw tissue) supplied by the National Research Council of Canada. Recoveries averaged 96.5 ± 18.2 % (n = 19). Analytical precision, determined using means of relative percent difference measurements, was 7.3 ± 6.7 % (n = 21 pairs). Accuracy determined by matrix spike recoveries averaged 96.4 ± 8.6 % (n = 21).

Results and Discussion

Soils

Bulk soil samples were collected September, 2007 from five managed wetlands within Suisun marsh to investigate spatial distribution of Hgt and MeHg and compare concentrations with other habitat types in Suisun marsh (Table 1, Figures 1 & 2). The average Hgt soil concentration for all samples was 0.11 ± 0.01 µg g^{-1} dw. Concentration of MeHg averaged 2.50 ± 0.97 ng g^{-1} dw. At the central sites 529 and 530 a comparison between samples collected at the surface and depth show a difference of a factor of two in Hgt concentrations but MeHg concentrations an order of magnitude higher at the surface. This observation is consistent with other studies showing Hg methylation to occur in the topmost portion of soils and sediments (Gilmour et al., 1992; Heim et al., 2007). Average Hgt concentrations of surface soils in the northern wetlands (Clubs 112 and 123) were 0.097 ± 0.01 µg g^{-1} dw compared to 0.148 ± 0.02 µg g^{-1} dw at the central wetlands (Clubs 525, 529, 530). Average MeHg concentrations are similar at northern (1.835 ± 0.515 ng g^{-1} dw) and central (4.374 ± 3.540 ng g^{-1} dw) Clubs considering the large variability between sites and clubs.

Table 1. Concentrations of Monomethylmercury (MeHg) and total mercury (Hgt) and the Percent MeHg/Hgt ratio in soil collected September, 2007 from five wetlands within Suisun marsh.

Station name	Date collected	Hgt $(ug/g)_{dry}$	MeHg $(ng/g)_{dry}$	Percent MeHg/Hgt
Club 112 site 1	9/10/2007	0.086	0.627	0.73
Club 112 site 2	9/10/2007	0.116	1.24	1.07
Club 112 site 3	9/10/2007	0.104	0.368	0.35
Club 123 site 1	9/10/2007	0.126	3.99	3.17
Club 123 site 2	9/10/2007	0.100	2.61	2.61
Club 123 site 3	9/10/2007	0.111	5.10	4.59
Club 123 site 4	9/10/2007	0.026	0.352	1.35
Club 123 site 5	9/10/2007	0.110	0.392	0.36
Club 525	9/10/2007	0.156	12.54	8.04
Club 529 Site 1 surface	9/10/2007	0.113	4.44	3.93
Club 529 Site 1 deep	9/10/2007	0.056	0.283	0.51
Club 530 Site 1 surface	9/10/2007	0.516	0.176	0.29
Club 530 Site 1 deep	9/10/2007	0.089	0.107	0.08

Measurements of mercury methylation and demethylation in soils using radioisotopes as described by (Marvin-DiPasquale and Agee, 2003) inform relative mercury methylation potentials of different sites and habitats. While these methods are preferred they were beyond the scope of this project. However, the ratio of MeHg to Hgt has been used as a proxy for mercury methylation potential (Gilmour et al., 1998; Heim et al., 2007; Kimball, 2006; Krabbenhoft and Wiener, 1999). In this approach the assumption is the larger the ratio the greater the potential for mercury methylation. The percent MeHg to Hgt ratios are listed in Table 1. The ratios range from 0.08 to 8.04 percent. The lowest value was observed in soil collected from depth and the highest value was from Club 525. A comparison of Clubs 112 (Percent MeHg/Hgt = 0.73 ± 0.207) and 123 (Percent MeHg/Hgt = 2.42 ± 0.732) show similar potential for mercury methylation given the uncertainties of the ratios. Soil collections as part of this project were generally used for screening and larger sample sizes would be needed to determine significant differences between the two Clubs.

We can use the Hg soil data collected to make comparisons to other habitat types within Suisun Marsh and upstream and downstream portions of the Estuary. Concentrations of Hgt in sediments within the managed wetlands were lower than observations from other locations within Suisun slough. In contrast, MeHg soil concentrations within managed wetlands are similar to measurements made at other locations around Suisun marsh. Table 2 lists a summary of Hgt and MeHg concentrations in sediment collected 2007 from locations in Suisun marsh (Stephenson and Heim, unpublished data). Sediment concentrations of Hgt were higher at the mouth of Suisun slough than at upper Suisun slough. However, MeHg concentrations were higher in the upper slough than at the mouth. Boynton slough Hgt concentrations were higher than Peytonia slough while both had elevated levels of MeHg compared to the mouth of Suisun slough.

Table 2. Concentrations of total mercury (Hgt) and Monomethylmercury (MeHg) in sediment collected winter 2007 from locations within Suisun marsh.

Station Name	**Date Collected**	**Hgt min (ug/g)**	**Hgt max (ug/g)**	**Hgt median (ug/g)**	**MeHg min (ng/g)**	**MeHg max (ng/g)**	**MeHg median (ng/g)**
Suisun Slough mouth	3/29/2007	.214	.361	.358	.236	.485	.300
Suisun Slough upper	3/28/2007	.202	.260	.238	1.80	2.51	2.19
First Mallard mouth	3/29/2007	.172	.286	.229	1.53	2.78	2.27
First Mallard upper	3/29/2007	.286	.367	.339	1.16	1.99	1.83
Peytonia Slough	3/28/2007	.082	.442	.141	.288	2.02	1.47
Boynton Slough	3/28/2007	.281	.607	.536	1.53	3.16	1.82

A comparison of Hgt concentrations in marsh sediments collected from locations within the San Francisco Bay Delta was reported by Heim et al., (2008). Figure 3 shows Suisun Bay marsh sediment Hgt concentrations in context to other San Francisco Bay Delta locations. Suisun Bay Hgt concentrations in sediments were lower than San Pablo Bay marsh sediments, were comparable to marsh sediments in the west Delta, and higher than marsh sediments in the central Delta.

Suisun Bay marsh sediment MeHg concentrations are shown in context of other marsh sediment concentrations across the San Francisco Bay Delta (Figure 4). Heim et al., (2008) reported concentrations in Suisun Bay marsh sediments that were much lower than what was found in marshes of San Pablo Bay, the west Delta, and south Delta. Suisun Bay marsh sediment MeHg concentrations were comparable to what was reported for marshes in the central Delta, northwest Delta and Cosumnes River.

Water

Water was collected from managed wetland clubs for the purpose of determining concentrations of MeHg in both filtered and unfiltered water. In addition during the first year of sampling suspended solids concentrations were also determined. This allowed the investigation of how MeHg concentrations changed as water moved onto the clubs and with changes in management practices on the clubs.

Figure 5 shows the locations water samples were collected from for Clubs 525, 529, 530 and Montezuma slough (MS). Concentrations of MeHg and SSC in water for Clubs 525, 529, 530, and MS are listed in Table 3. At wetland 525 and 529 no change in MeHg concentrations were observed in filtered or unfiltered water. At wetland 525 SSC concentrations decreased with time after flood-up and at wetland 529 SSC was highly variable. At wetland 530 MeHg and SSC concentrations increased with time after flood-up. Concentrations of MeHg at MS were lower than what was observed in water collected from the Club sites.

Table 3. Concentrations of monomethylmercury (MeHg) and suspended solids (SSC) in water collected from October to November, 2007 at wetlands 525, 529, 530 and Montezuma slough (MS).

Site	**Date**	**MeHg Unfiltered (ng/ L)**	**MeHg Filtered (ng/L)**	**SSC (mg/ L)**
wetland 525-GWQ-1	10/17/07	0.216	0.172	9.677
wetland 525-GWQ-1	11/5/07	0.269	0.233	2.817
wetland 525-GWQ-1	11/19/07	0.303	0.205	<MDL
wetland 529-GWQ-1	10/17/07	1.02	0.116	32.22
wetland 529-GWQ-1	11/5/07	1.21	0.277	3.279
wetland 529-GWQ-1	11/19/07	0.914	0.319	33.03
wetland 530-GWQ-1	10/17/07	0.707	0.251	5.319
wetland 530-GWQ-1	11/5/07	3.04	0.34	8.772
wetland 530-GWQ-1	11/19/07	3.61	0.846	30.00
MS-GWQ-1	10/17/07	.023	<MDL	6.410
MS-GWQ-1	11/5/07	0.107	0.05	10.34
MS-GWQ-1	11/19/07	0.093	0.028	28.30

Year one Club 112 unfiltered MeHg concentrations are shown in Figure 6. A comparison is made between edge sites 1 and 2 (North) and edge site 3 (South). Site 3 is the fresh water source for Club 112. Figure 6 shows MeHg concentrations are initially elevated at the northern sites relative to the southern site. At the interior sites GWQ-4, 5, and 8 MeHg concentrations were elevated one to two months after flood-up before decreasing. Dissolved MeHg concentrations at Club 112 for the same locations and time are shown in Figure 7. Illustrated is a clear initial increase in the dissolved MeHg concentrations after the Club 112 flood-up. Concentrations are elevated at the northern sites relative to the fresh water source at the south. After several months the concentrations decrease and are similar to the source water. Also, the same pattern occurred at all interior sites. A measure of the suspended sediment at Club 112 is shown in Figure 8. SSC was higher at GWQ-1 relative to the source water at GWQ-3 however GWQ-2 had similar SSC resulting in no clear north/south gradient. The highest SSC was observed in the interior of the Club. The concentration of MeHg on suspended particulates is calculated by the following equation:

$$[MeHg]_{suspended\ particulate} = [MeHg]_{unfiltered} - [MeHg]_{filtered} / SSC$$

Figure 9 shows the calculated concentrations of MeHg for suspended sediment in Club 112. Concentrations were typically higher at the northern sites GWQ- 1 & 2 relative to the southern site GWQ-3 and interior sites had similar concentrations to the northern edge sites.

Year two Club 112 unfiltered MeHg concentrations are shown in Figure 10. The same comparison between edge and interior sites and northern and southern sites shows the following: (1) MeHg concentrations were once again higher at the northern sites GWQ-1 & 2 relative to GWQ-3, and (2) interior site MeHg concentrations were higher relative to the source water. In year two MeHg concentrations at the northern sites did not decrease with time as they did in year one but remained elevated relative to GWQ-3. Dissolved MeHg concentrations for year two at Club 112 are shown in Figure 11. Dissolved concentrations were initially higher at the northern sites GWQ-1 & 2 relative to the south site GWQ-3 but rapidly decreased to similar concentrations for the remainder of year two sampling. No clear increase in MeHg concentration after flood up of Club 112 was observed as was the case for year one. Generally, concentrations at Club 112 were similar between year one and two.

Concentrations of MeHg in unfiltered water collected year one at wetland 123 are shown in Figure 12. Sample sites are split into edge and interior locations. At Club 123 water typically flows from north to south. There is also a fresh water source located at GWQ-7. This site had consistently low MeHg concentrations. The highest concentrations were observed at GWQ-4 at the southeast corner of the club. Concentrations at this site were initially an order of magnitude higher than other sites but decreased over time. Interior sites show an increase in MeHg concentrations after flood up followed by a decrease with time after one month. Figure 13 shows dissolved MeHg concentrations follow a similar pattern as the unfiltered MeHg. SSC after flood up at Club 123 is initially higher at the southern edge sites relative to the northern edge sites with the exception of the freshwater source GWQ-7 (Figure 14). After the first month SSC was similar at all edge sites. SSC at interior sites decreased slightly during year one sampling (Figure 14). Concentrations of MeHg on suspended particulates for Club 123 was calculated as described above. Figure 15 shows the concentrations of MeHg on suspended particulates at Club 123 for year one. Similar to unfiltered water at the freshwater source concentrations of MeHg on particulates was low compared to the southeastern site GWQ-4. All other edge sites had concentrations between ~10-100 ng g^{-1} for the entire sampling period. The highest concentrations were observed at the interior site GWQ-17 at the southwestern corner of the Club.

Year two sampling at Club 123 captures the flood up event as it relates to MeHg production. Figure 16 shows unfiltered MeHg concentrations for edge and interior sampling sites. Initially all edge sites have low MeHg concentrations. A clear spike in concentration (1 – 7 ng L^{-1}) is observed for edge sites the following week. Concentrations then decrease to less than 1 ng L^{-1} the following two weeks. After several months MeHg concentrations at site GWQ-4 are again elevated to around 4 ng L-1 with other sites being 0.2 – 2 ng L^{-1}. A similar pattern is observed at the interior sites and in the dissolved concentrations (Figure 16 & Figure 17).

Club 123 had the highest MeHg concentrations measured compared to other wetlands sampled in this study. Although both Clubs 123 and 112 had elevated concentrations compared to the central Clubs 525, 529, and 530. All managed wetlands sampled in this study showed elevated levels of MeHg when compared to MS.

A summary of Hgt and MeHg concentrations in unfiltered water collected 2005-2006 from locations within Suisun marsh is listed in Table 4 (Stephenson and Heim, unpublished data). Total mercury concentrations ranged from ~7 to 37 ng L^{-1}. Concentrations of MeHg ranged from 0.08 to 0.4 ng L^{-1}. Although the timing of sampling differs a broad comparison is made between samples collected from tidal marshes within Suisun marsh (Table 4) and those collected from within the managed wetlands (This study). In summary, the tidal wetlands and the managed wetland have similar MeHg concentrations if comparing the time period several months after flood up. During the initial flood up period the managed wetlands have higher MeHg concentrations than what was observed at the tidal marsh sites.

Table 4. Concentrations of total mercury (Hgt) and monomethylmercury (MeHg) in unfiltered water collected from locations within Suisun marsh for the years 2005 to 2006.

Station Name	Date Collected	Hgt (ng/L)	MeHg (ng/L)
Suisun Slough	6/28/2005	36.62	.112
First Mallard	6/28/2005	26.33	.329
Suisun Slough	5/2/2006	6.7	.078
First Mallard	5/2/2006	13.31	.306
Peytonia Slough	9/5/2006	11.13	.419
Boynton Slough	9/5/2006	10.81	.174

Laboratory Studies

Experiment number 1 was conducted in microcosms to investigate the relationships between vegetation, dissolved oxygen, and MeHg. The following treatments were set up in triplicate: (1) preflooded soil plus swamp timothy, (2) preflooded soil only, (3) soil plus swamp timothy, and (4) soil only. Preflooded treatments were started six days prior to non-preflooded treatments by adding and removing water and then allowing the soils to remain wet prior to re-flooding. Figure 18 shows resulting MeHg concentrations in the microcosms for the treatments. The initial sampling shows the pre-flood plant plus soil treatment to have a higher MeHg concentrations than other treatments indicating the production of MeHg occurred either during the six days prior to the final flood-up or during the equilibration period. The pre-flooded plant plus sediment treatment continued to increase MeHg concentration through day seven of the experiment. The plant plus sediment treatment also increased MeHg concentration but more gradually over a longer time period and a lesser magnitude. Soil only treatments did not show the same increase in MeHg as the plant plus soil treatments. No significant relationship was observed between oxygen concentration and MeHg concentrations for treatments which were not pre-flooded. However, Figure 19 shows a negative significant correlation ($r^2 = 0.74$, $p = 0.03$) between MeHg and oxygen for preflooded treatments of plant plus soil and soil only. Lower oxygen concentrations resulted in higher MeHg concentrations. In summary, microcosms which were preflooded resulted in higher MeHg concentrations in the presence of vegetation.

Treatments without vegetation added did not show the same ability to produce MeHg regardless of pre-flooding. Oxygen concentrations are a factor influencing MeHg production in preflooded treatments.

In experiment number 2 microcosms were used to investigate the relationship between varying plant material and sediment under aerated and non-aerated conditions with a single time point of sampling. Figure 20 shows the results of all samples looking at the varying amount of vegetation and the resulting MeHg concentrations for both aerated and non-aerated samples. For any given treatment of vegetation addition the non-aerated samples resulted in a higher concentration of MeHg. Furthermore, the addition of 8 grams of plant material resulted in higher concentrations of MeHg for both aerated and non-aerated treatments. Figure 21 shows the relationship between percent oxygen saturation and MeHg for the non-aerated treatments. The relationship was significant ($r^2 = 0.75$, $p < 0.001$) with decreased percent oxygen saturation MeHg concentrations were increased.

This data can be analyzed using statistical methods to answer various questions related to the interaction of plant material, soil, and MeHg production[1]. First, looking at the non-aerated treatments with up to 2 grams of vegetation added the following questions were asked: a) Does increasing sediment result in increasing methyl mercury? b) Does increasing vegetation result in increasing methyl mercury?, and c) Is there evidence for a cross product (i.e. more sediment produces a disproportionate amount of MeHg at increasing vegetation levels or vice versa?). A Kruskal Wallis test indicated there was no statistical difference for changes in sediment concentration. The addition of more sediment does not produce more MeHg. Coupled with results from experiment 1 this indicates some sediment is needed for the MeHg process to occur but continued additions does not increase MeHg concentrations in the microcosms.
A kruskal wallis test with up to 2 g of vegetation added demonstrates that MeHg concentrations with 0 g vegetation treatment is statistically less than the other two. The two higher treatments are not different from each other. So, the conclusion appears to be that the process is sensitive to the addition of some vegetation material but after that the response is slight over the length of our experiment. Considering changes in sediment and vegetation together show that higher MeHg concentrations occur with increasing vegetation above 0 g and indicate not much else was important.

The analysis was then extended to include the 4 and 8 g additions of vegetation for 240 g additions of non-aerated soil. The following question was asked: Does increasing the mass of vegetation result in increasing MeHg concentrations? Again, a non parametric test was used as ANOVA did not meet assumptions. MeHg concentrations increased steadily as a function of increasing vegetation but only the highest treatment was statistically different from no vegetation. This is the same general result as described previously. Overall, more vegetation results in more MeHg over the time frame studied.

Next, the analysis was repeated with aerated treatments and 2 g of added vegetation. The question is "Does increasing sediment concentration increase MeHg under aeration and 2-g of added vegetation?". Using ANOVA the conclusion is that increasing sediment did not increase MeHg levels. This same analysis is extended to include an increase in mass of vegetation added

[1] We acknowledge Chris Foe for guidance and work setting up statistical analysis of Experiment 2 data.

to the microcosms with the following question, "Does increasing vegetation increase MeHg under aeration and 240 g sediment?". Again, using ANOVA the conclusion is that increasing vegetation does increase MeHg levels. The 8 g plant addition treatment is statistically different than both the 4 and 2 g levels. The latter two are not different from each other. This result is similar to that obtained with vegetation under anaerobic conditions and suggests that the pickle microcosms are sensitive to an increase in organic material.

Finally, we looked at the effect of aeration on MeHg concentrations. The following questions are asked: a) Does aeration change MeHg concentration under constant vegetation (2g) but varying sediment?, and b) Does aeration change MeHg concentration under constant sediment concentrations (240g) but varying vegetation levels? Increasing sediment levels between 75 and 240 g were analyzed with and without aeration at a constant vegetation level of 2 grams. A Kruskal Wallis test was used as the results did not meet the assumptions of an ANOVA. Overall, aeration reduced MeHg production. The second question was answered by analyzing the MeHg concentrations at increasing concentrations of vegetation treatments with and without aeration and at a fixed sediment level (240 g). The assumptions of an ANOVA were violated so several kruskal-wallis tests were used. These showed that increasing concentrations of vegetation resulted in increasing MeHg levels. No aeration also resulted in more MeHg. These results are similar to those obtained previously and confirm their robustness. No aeration and more vegetation results in higher MeHg concentrations.

Conclusions

MeHg and Hgt in sediments and soils in Suisun Marsh and managed wetlands were similar to those found in other parts of the Delta and San Pablo Bay. MeHg in water in Suisun Marsh was much higher than in other parts of the Delta especially during times of the year when managed wetland floodup occurs. High concentrations of MeHg occur within two weeks of initial floodup then tapers off to a lower level about 2 months later. Initial experiments in the laboratory indicated that a prewetting period of about a week before final floodup still produced about the same MeHg concentrations in the water after the second flood up indicating prefloodup would not work for a BMP to reduce MeHg concentrations. The MeHg concentrations in floodup waters were negatively correlated with oxygen levels indicating microbial activity was driving both process. In laboratory experiments the amount vegetation was related to the amount of oxygen depleted and the amount of MeHg produced. More vegetation translated into higher MeHg concentrations and less oxygen.

Recommendations

Best Management Practices

1) Limit vegetation biomass on managed fields
    a. Graze managed fields with cattle during summer months
    b. Use irrigation practices to favor low biomass plants
    c. Use herbicides to kill unwanted plants on fields before they increase in biomass
2) Limit amount of water exported during first two months after floodup

3) Place oxygen meter in slough channels and have managers discharge only when oxygen levels are high—this will also limit discharges of high levels of MeHg
4) Stagger discharges in the post duck season drain down.

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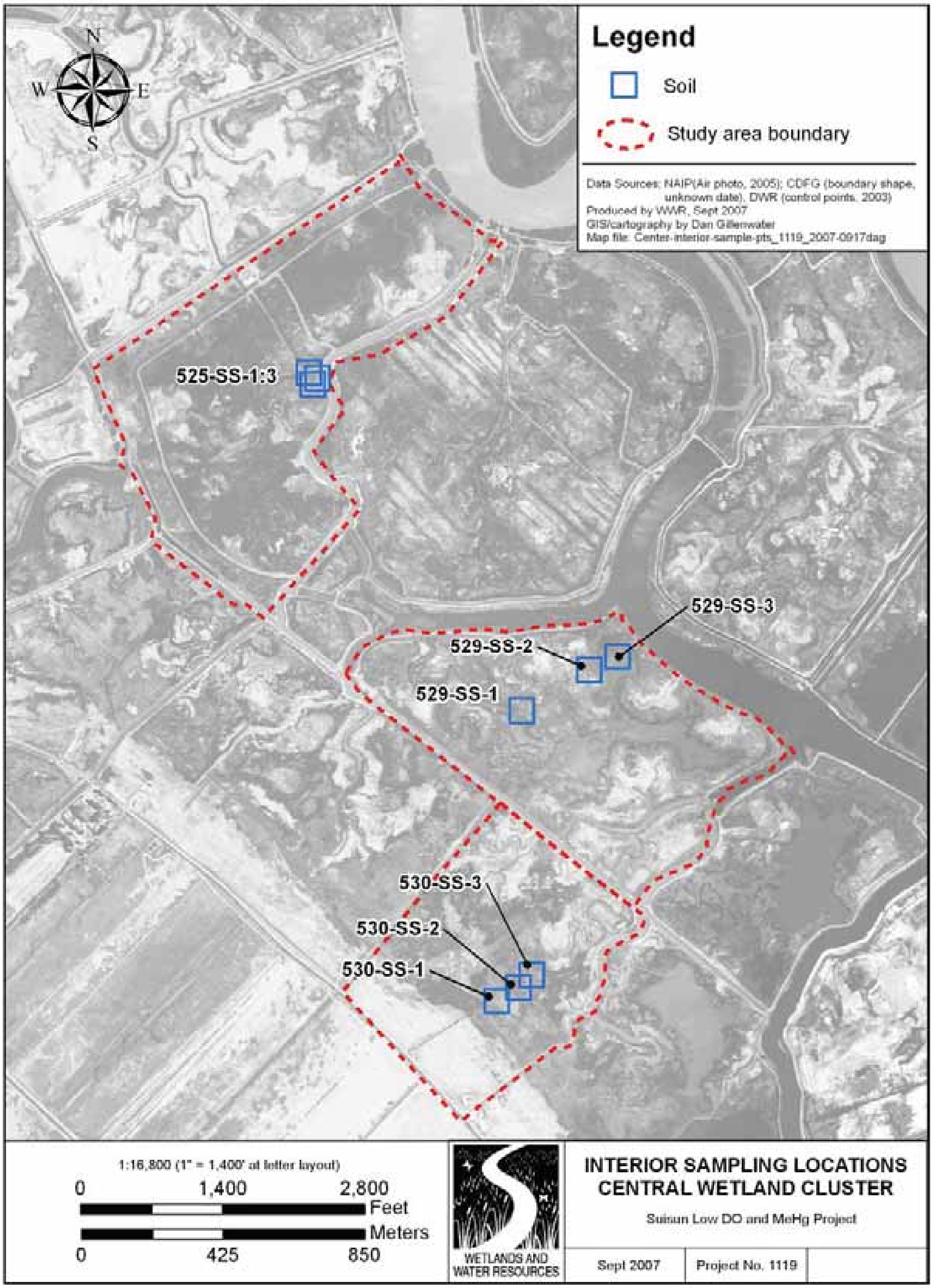


Figure 1. Map showing sediment sampling locations in wetlands 525, 529, and 530.

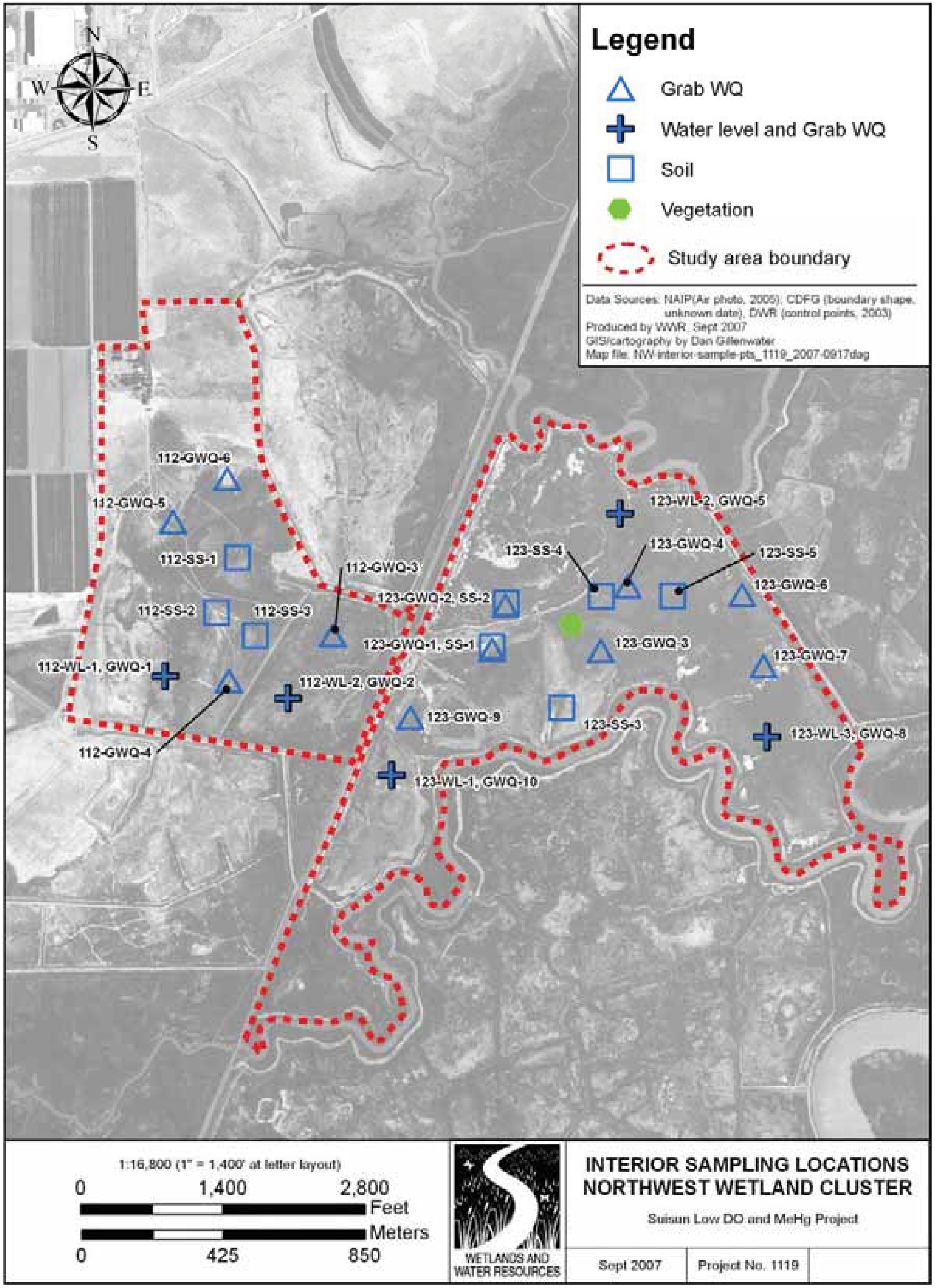


Figure 2. Map showing sediment and water grab sampling locations in wetlands 112, and 123.

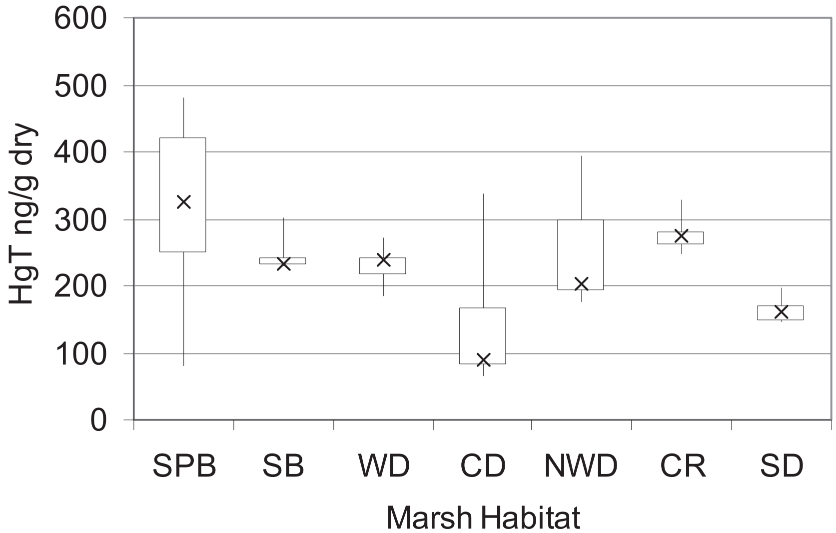


Figure 3. Total mercury (Hgt) sediment concentrations (ng g^{-1} dry) in samples collected from marsh habitat of San Pablo Bay (SPB), Suisun Bay (SB), West Delta (WD), Central Delta (CD), Northwest Delta (NWD), Cosumnes River (CR), and South Delta (SD). The median concentration is represented by ‘*’. Vertical lines represent maximum and minimum concentrations. Boxes are bracketing lower and upper quartile (Figure from Heim et al, 2008).

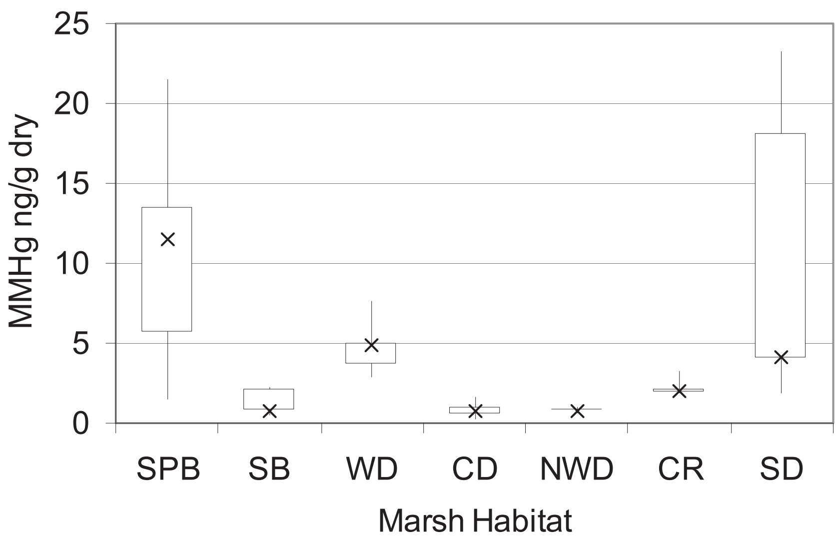


Figure 4. Methylmercury (MMHg) sediment concentrations (ng g^{-1} dry) in samples collected from marsh habitat of San Pablo Bay (SPB), Suisun Bay (SB), West Delta (WD), Central Delta (CD), Northwest Delta (NWD), Cosumnes River (CR), and South Delta (SD). The median concentration is represented by ‘*’. Vertical lines represent maximum and minimum concentrations. Boxes are bracketing lower and upper quartile (Figure from Heim et al, 2008).

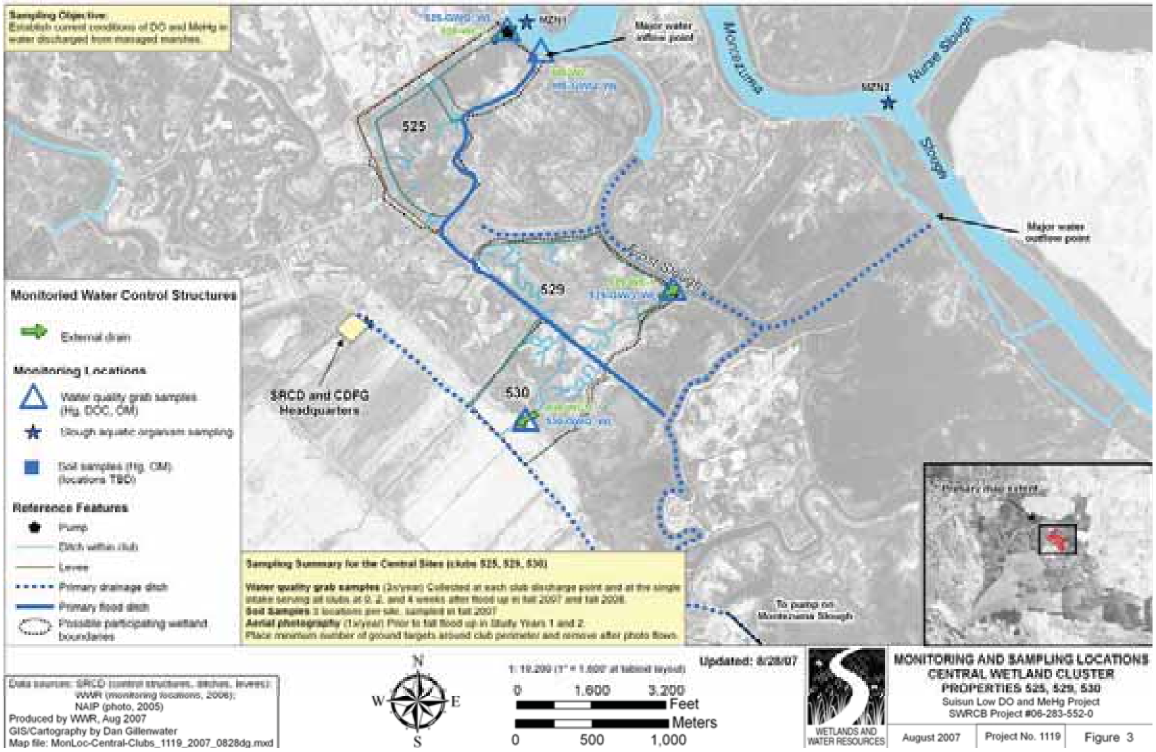


Figure 5. Map showing water grab sampling locations in wetlands 525, 529, and 530.

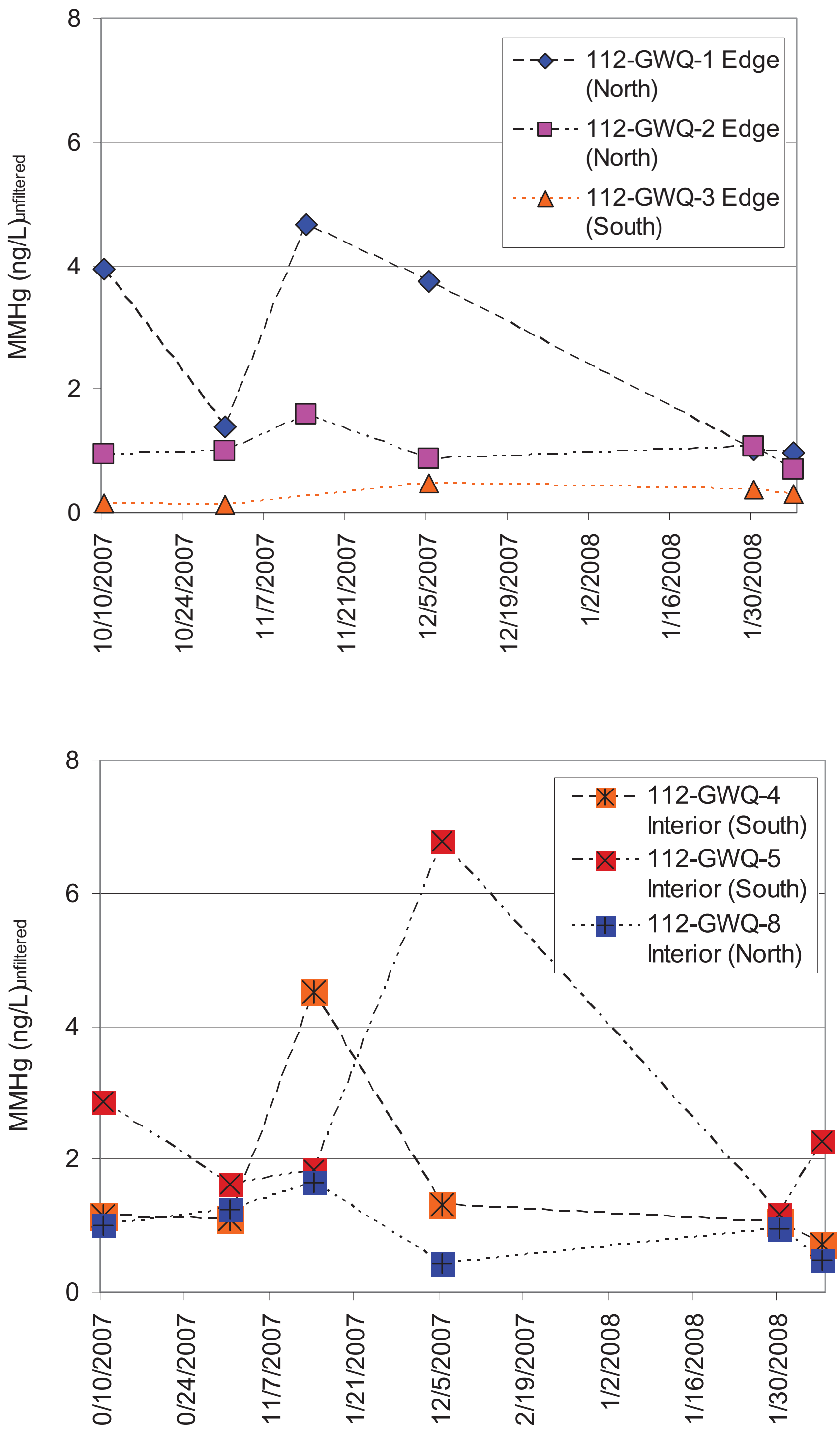


Figure 6. MeHg concentrations in unfiltered water collected year one from the edge (upper panel) and interior (lower panel) at Club 112; shows MeHg concentrations increasing in the direction of water movement at the edge locations (south to north) and higher concentrations at the interior sites relative to source water.

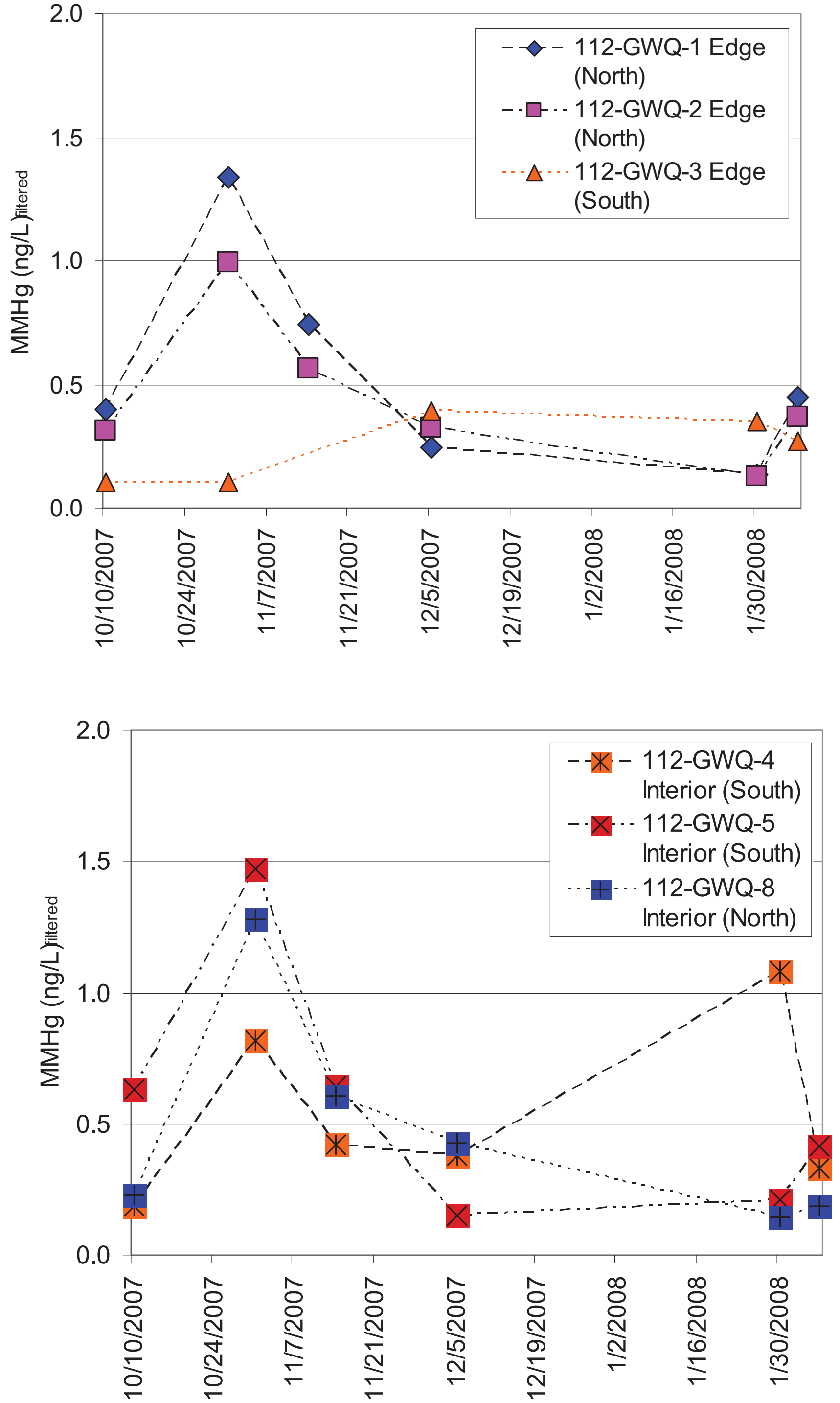


Figure 7. MeHg concentrations in filtered water collected year one from the edge (upper panel) and interior (lower panel) at Club 112; shows MeHg concentrations initially increasing in the direction of water movement at the edge locations (south to north) with higher concentrations at the interior sites relative to source water.

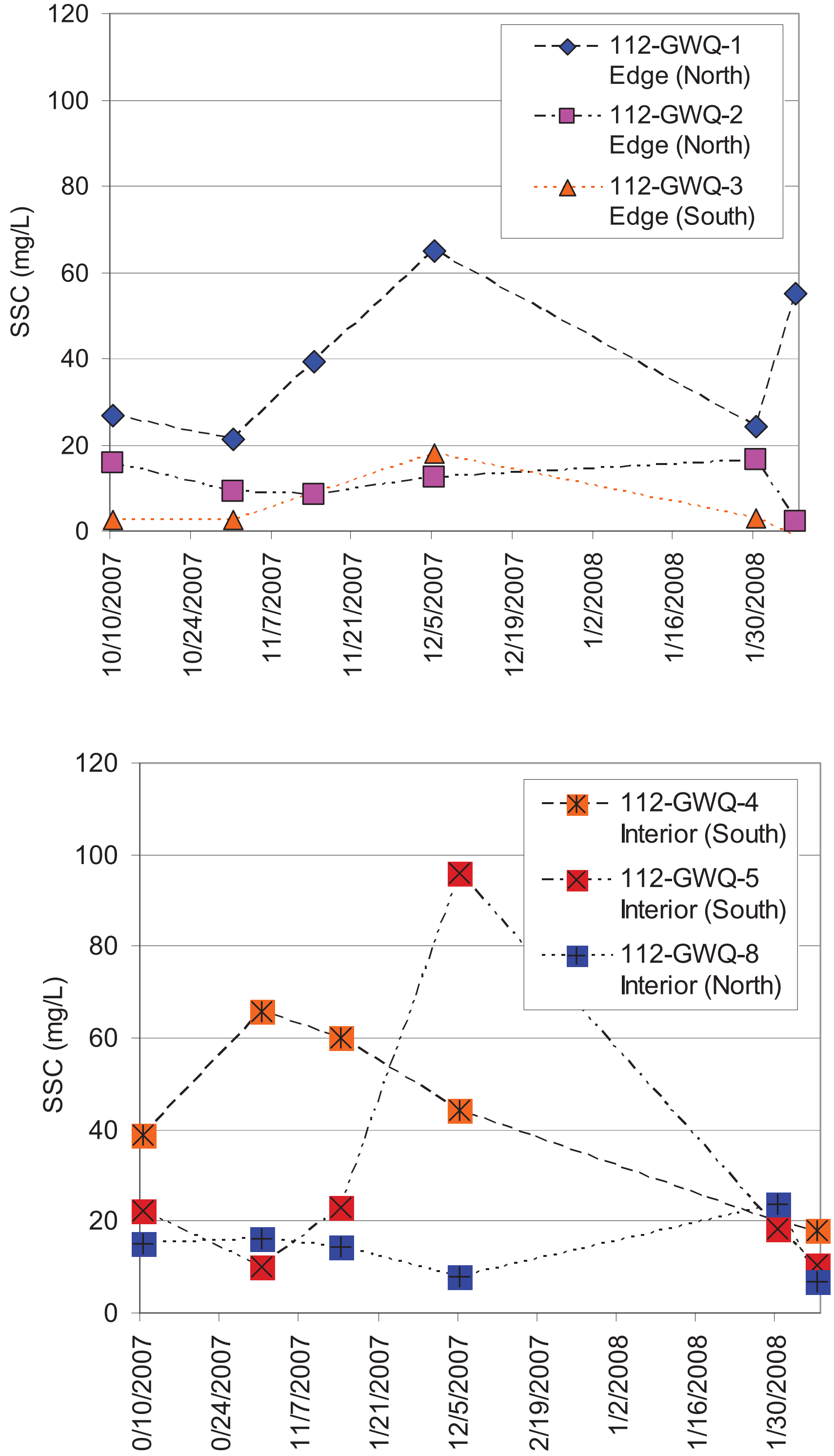
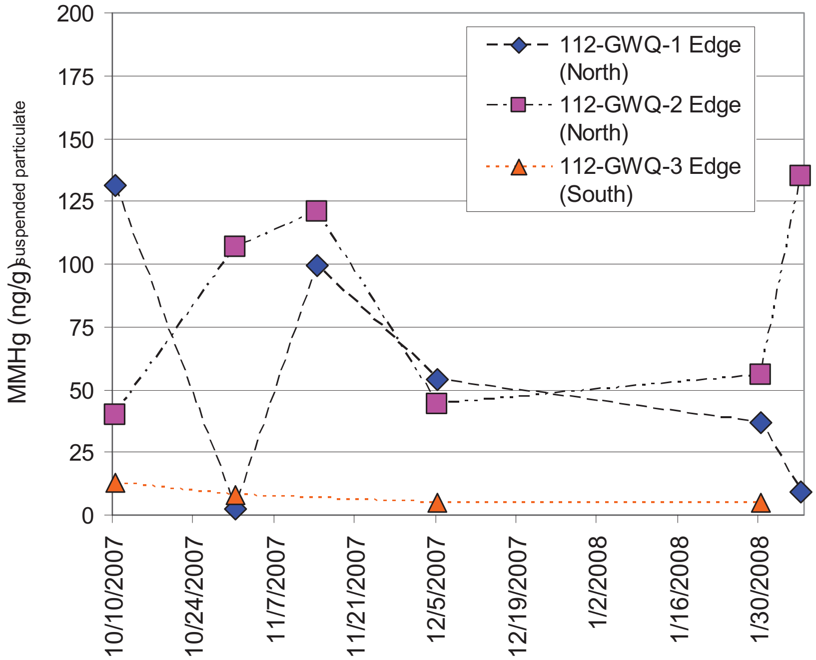


Figure 8. Suspended sediment concentrations (SSC) in filtered water collected year one from the edge (upper panel) and interior (lower panel) at Club 112.



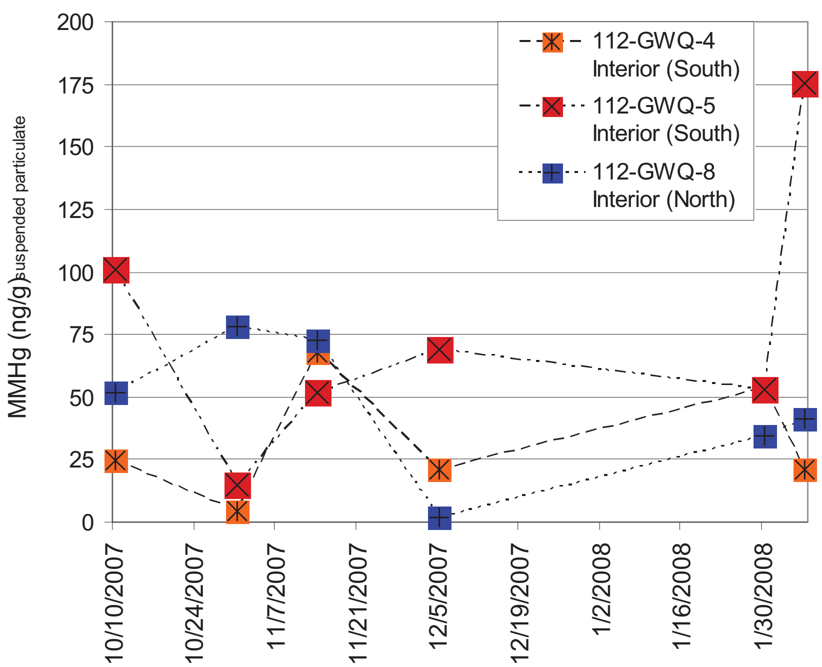


Figure 9. MeHg concentrations calculated for suspended sediment from the edge (upper panel) and interior (lower panel) at Club 112; shows MeHg concentrations increased in the direction of water movement at the edge locations (south to north) with higher concentrations at the northern edge relative to the interior and southern edge.

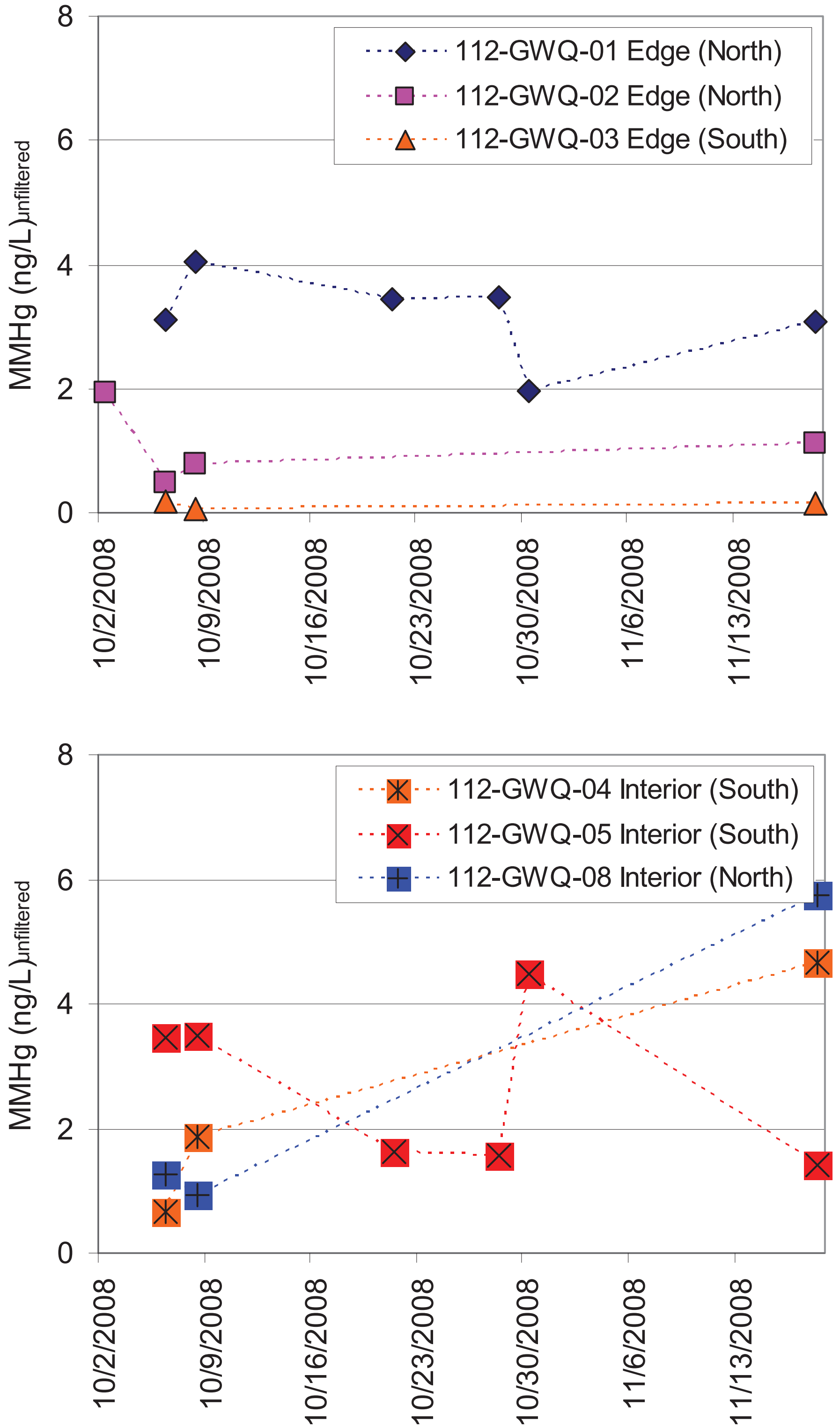


Figure 10. MeHg concentrations in unfiltered water collected year two from the edge (upper panel) and interior (lower panel) at Club 112; shows MeHg concentrations increasing in the direction of water movement at the edge locations (south to north) and higher concentrations at the interior sites relative to source water.

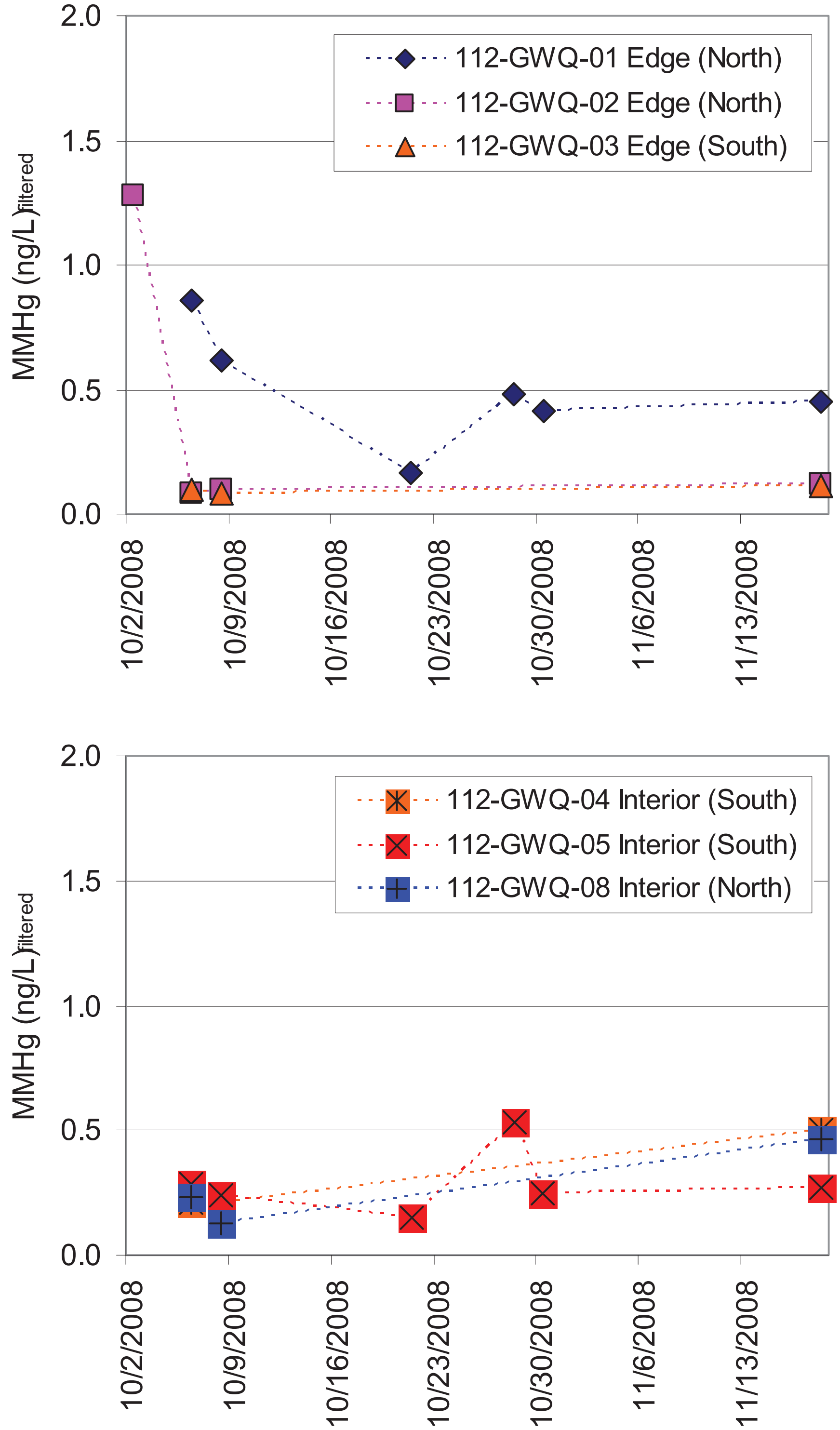


Figure 11. MeHg concentrations in filtered water collected year two from the edge (upper panel) and interior (lower panel) at Club 112.

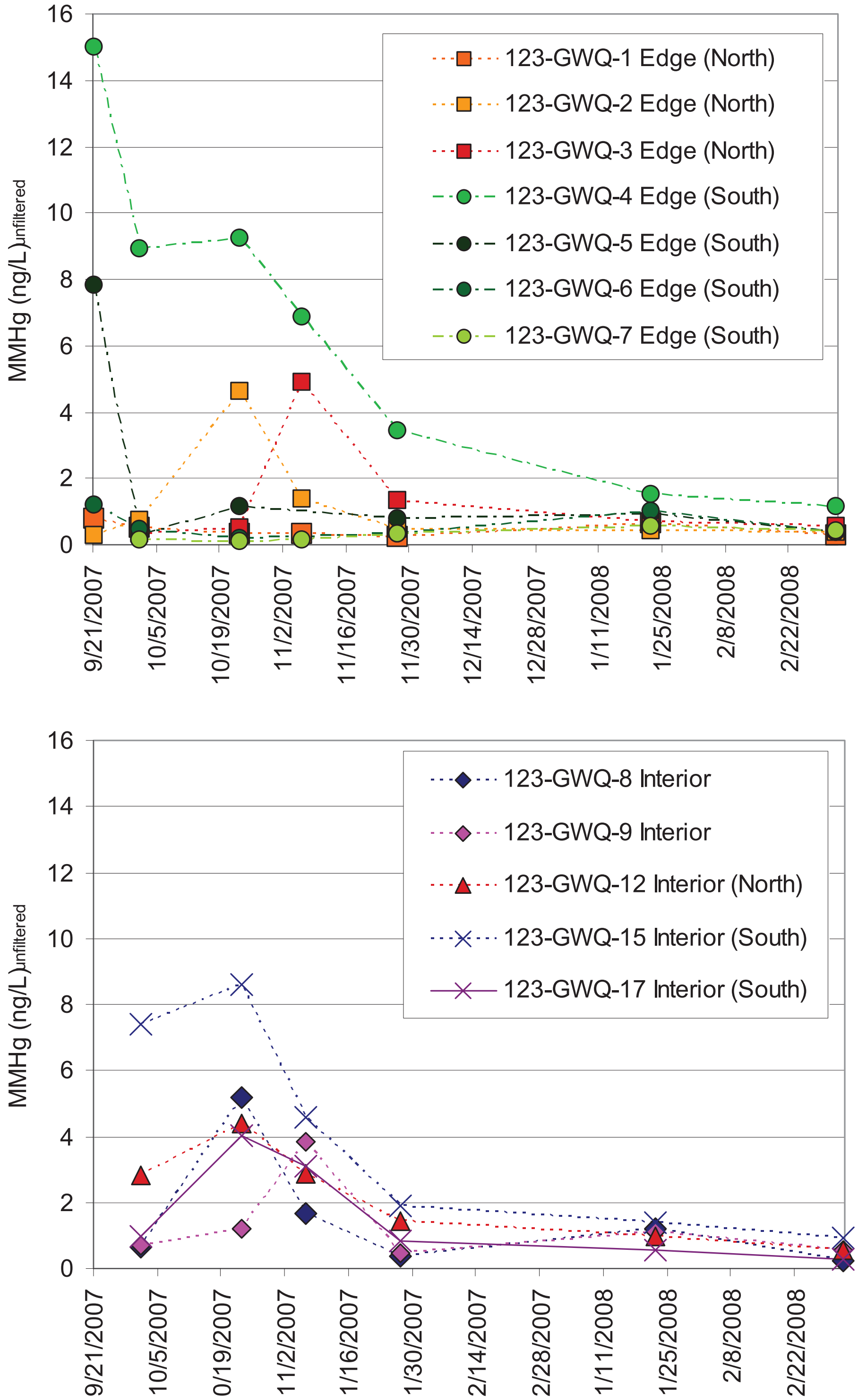


Figure 12. MeHg concentrations in unfiltered water collected year one from the edge (upper panel) and interior (lower panel) at Club 123. Shows the freshwater source GWQ-7 is low in concentration, GWQ-4 at the southeast is the high in concentration, and interior sites have an initial peak in MeHg concentration and then decrease over time.

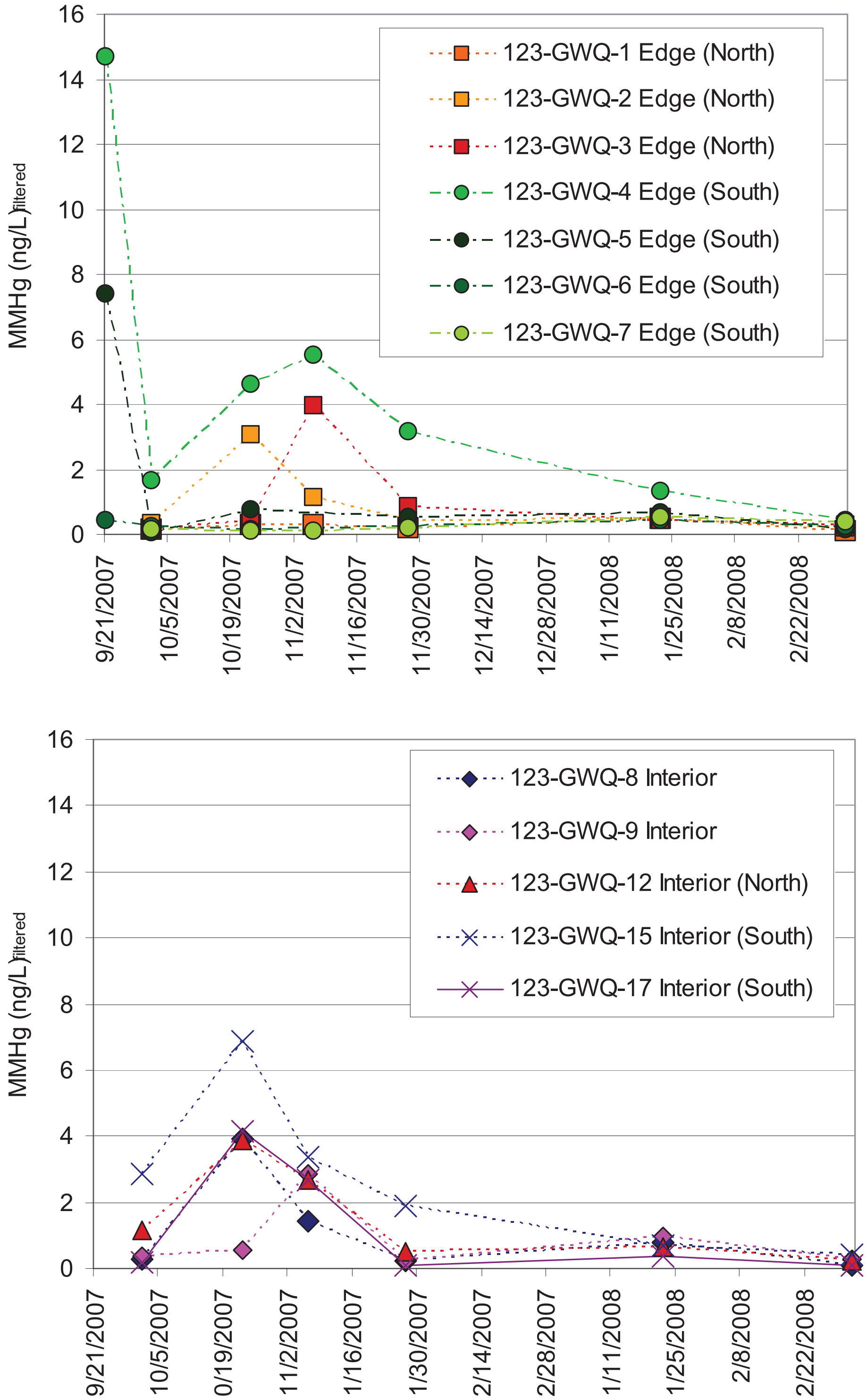


Figure 13. MeHg concentrations in filtered water collected year one from the edge (upper panel) and interior (lower panel) at Club 123. Shows the freshwater source GWQ-7 is low in concentration, GWQ-4 at the southeast is the high in concentration, and interior sites have an initial peak in MeHg concentration and then decrease over time.

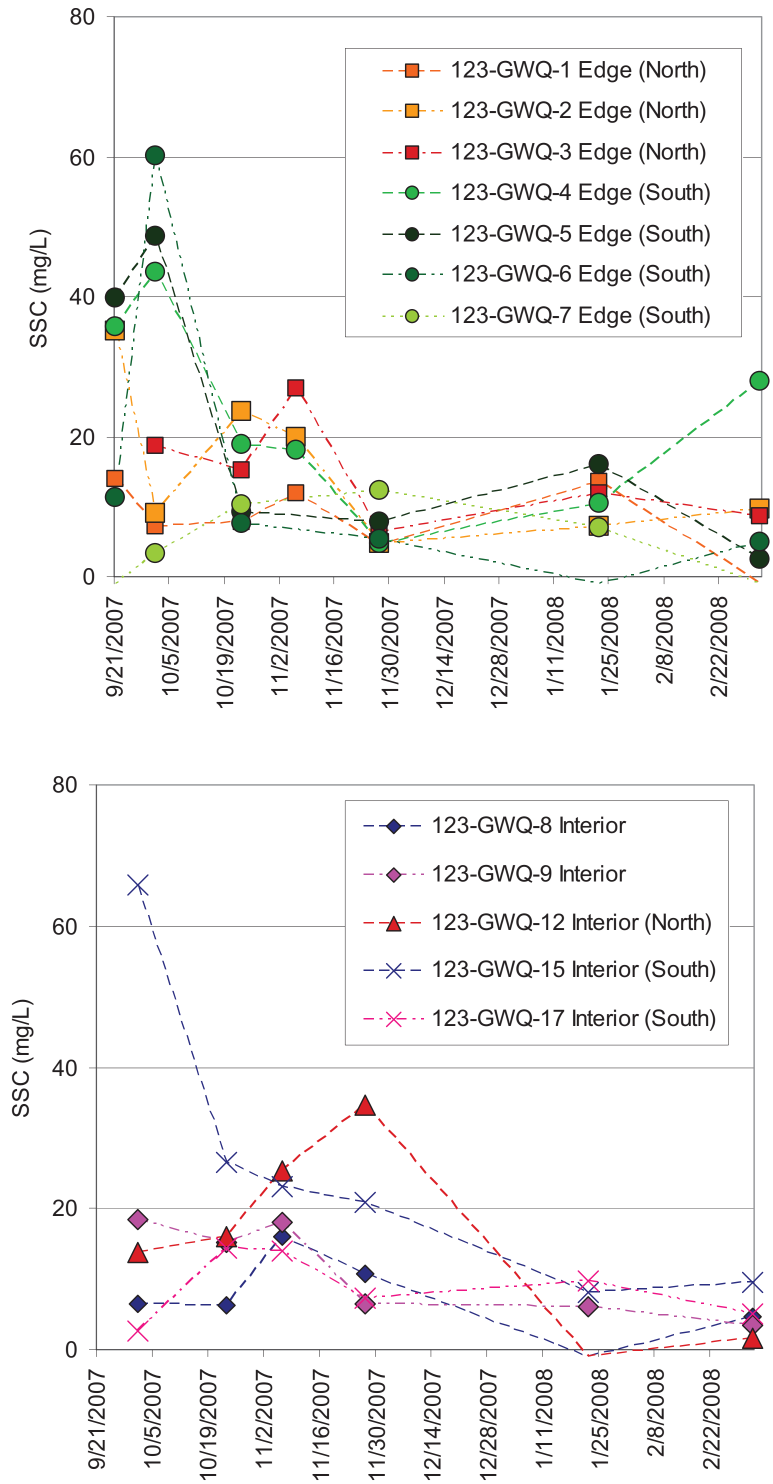


Figure 14. Suspended sediment concentrations (SSC) in filtered water collected year one from the edge (upper panel) and interior (lower panel) at Club 123.

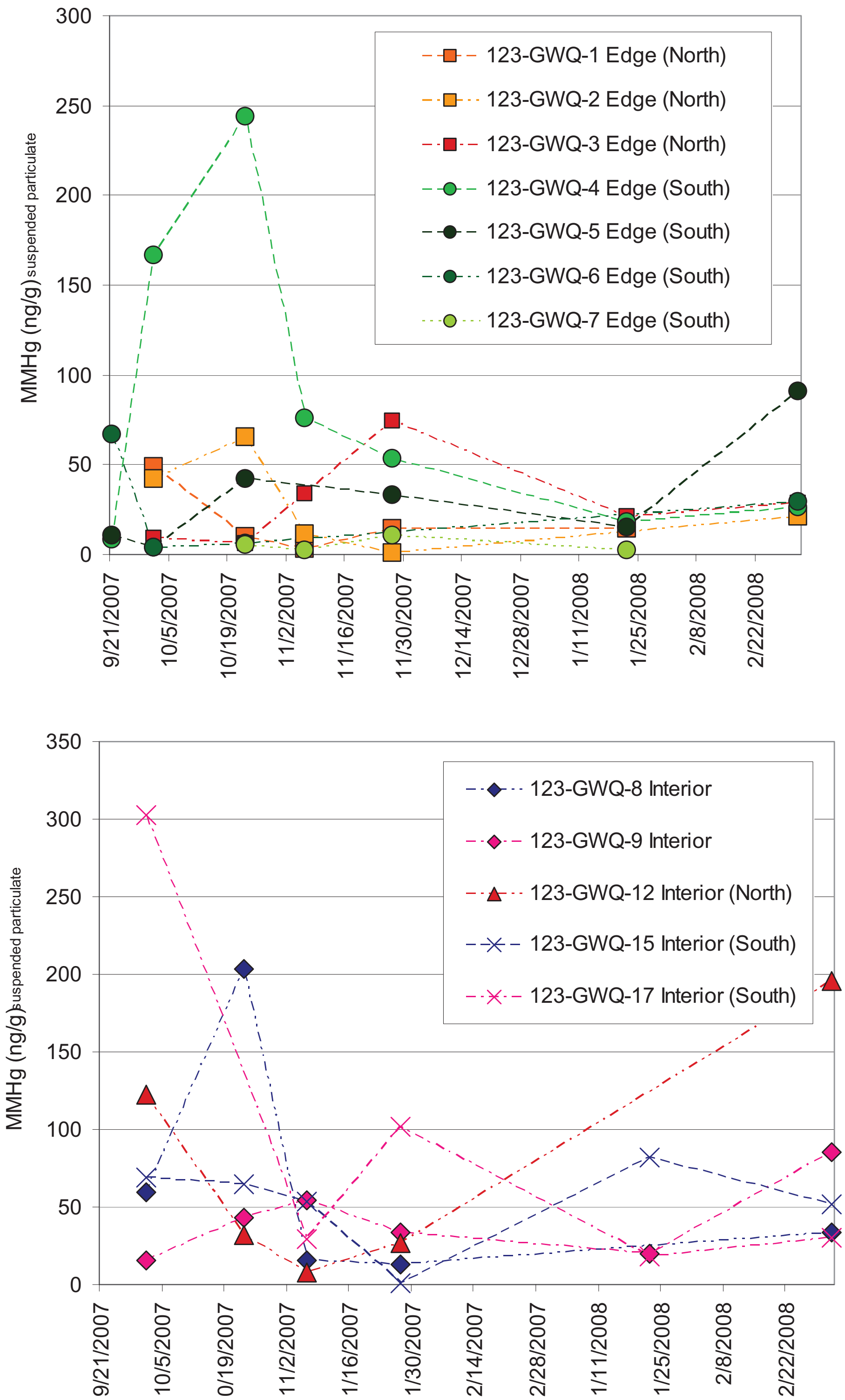


Figure 15. Year one MeHg concentrations calculated for suspended sediment from the edge (upper panel) and interior (lower panel) at Club 123.

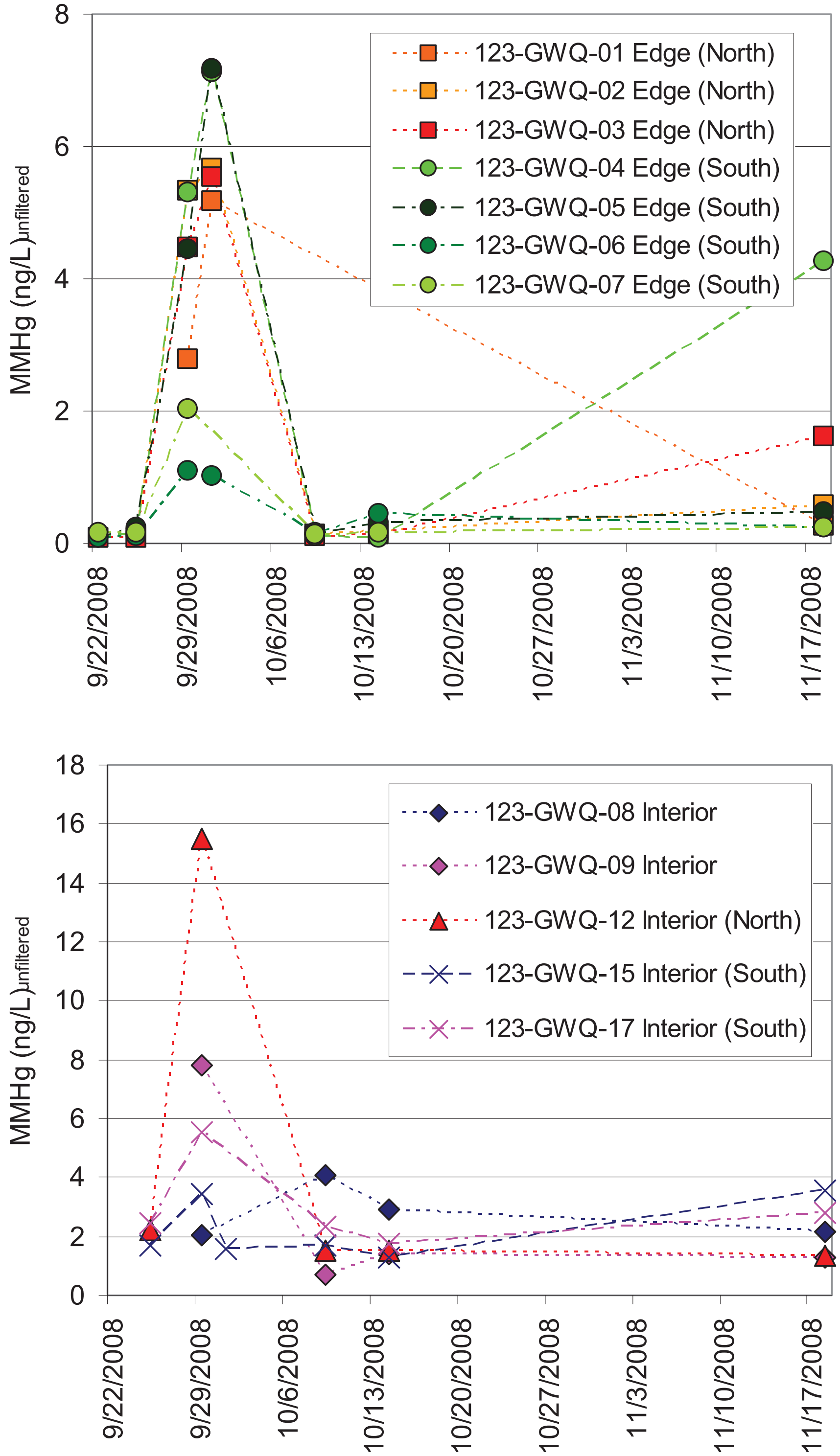


Figure 16. MeHg concentrations in unfiltered water collected year two from the edge (upper panel) and interior (lower panel) at Club 123. Shows MeHg rapidly increases and decreases after flood up.

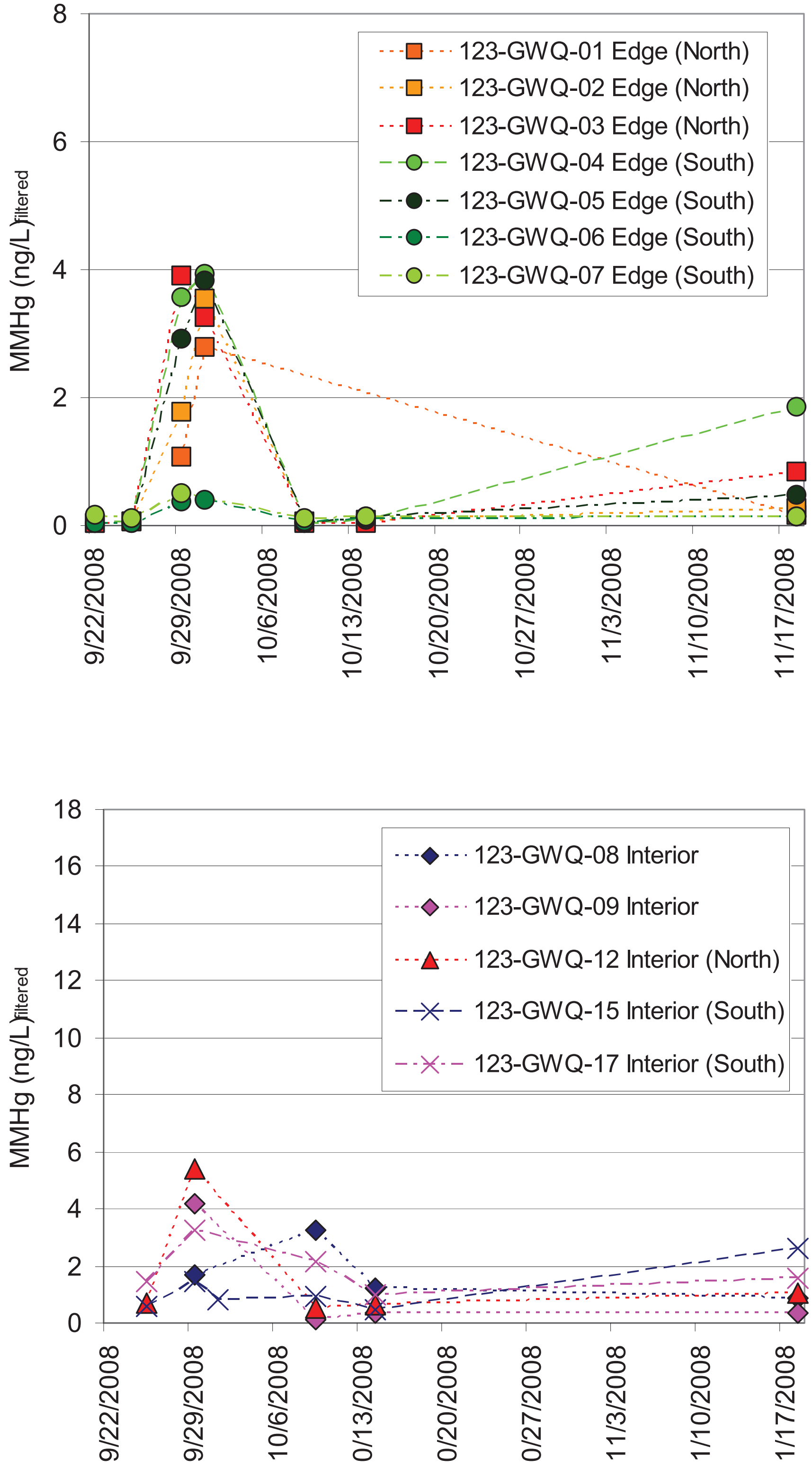


Figure 17. MeHg concentrations in filtered water collected year two from the edge (upper panel) and interior (lower panel) at Club 123. Shows MeHg increases and decreases rapidly after flood up.

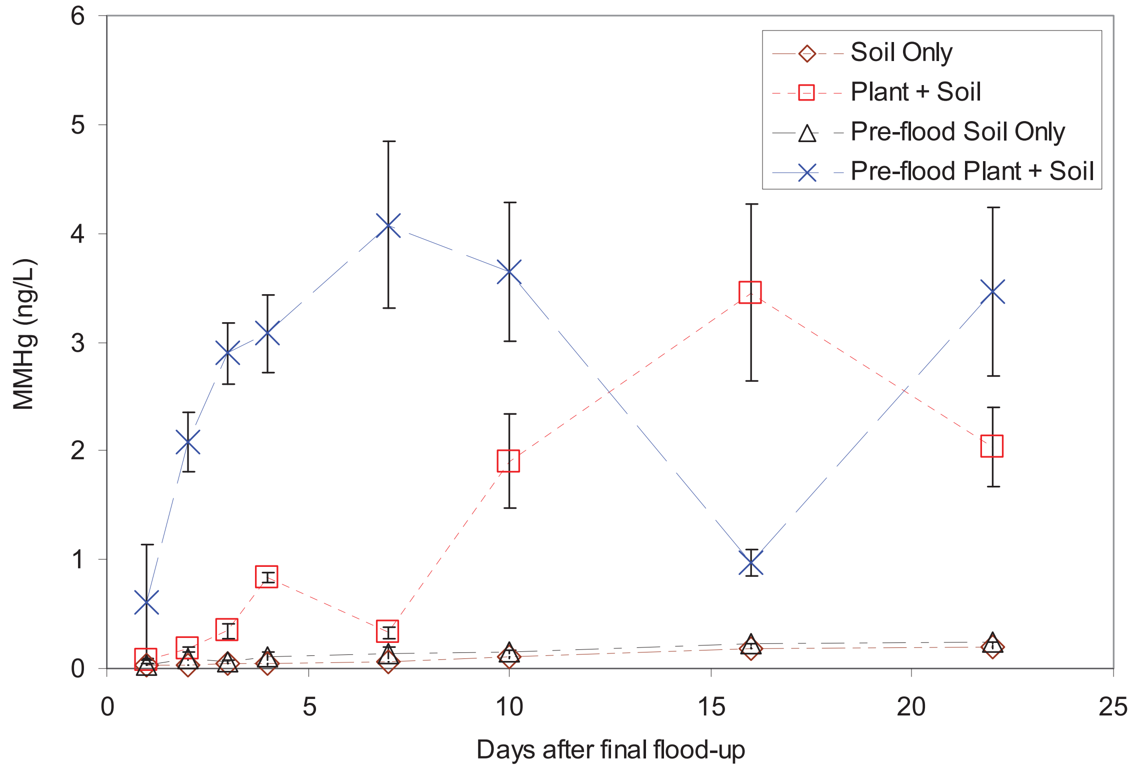


Figure 18. Average methymercury (MeHg) concentrations in microcosms over time for the following four treatments: (-◊-) soil only, (-□-) plant plus soil, (-Δ-) pre-flood soil only, and (-X-) pre-flood plant plus soil. Error bars are standard error of experimental triplicates.

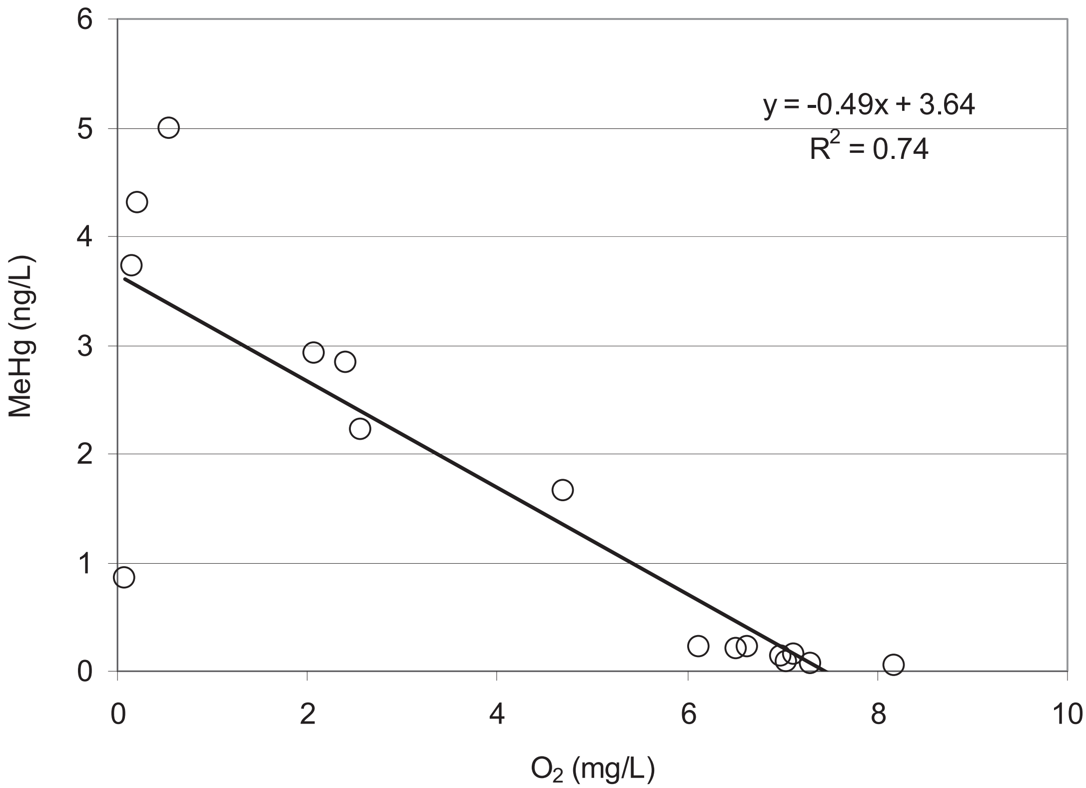


Figure 19. Relationship between MeHg and oxygen for preflooded treatments of plant plus soil and soil only was observed to be significant ($p < 0.05$).

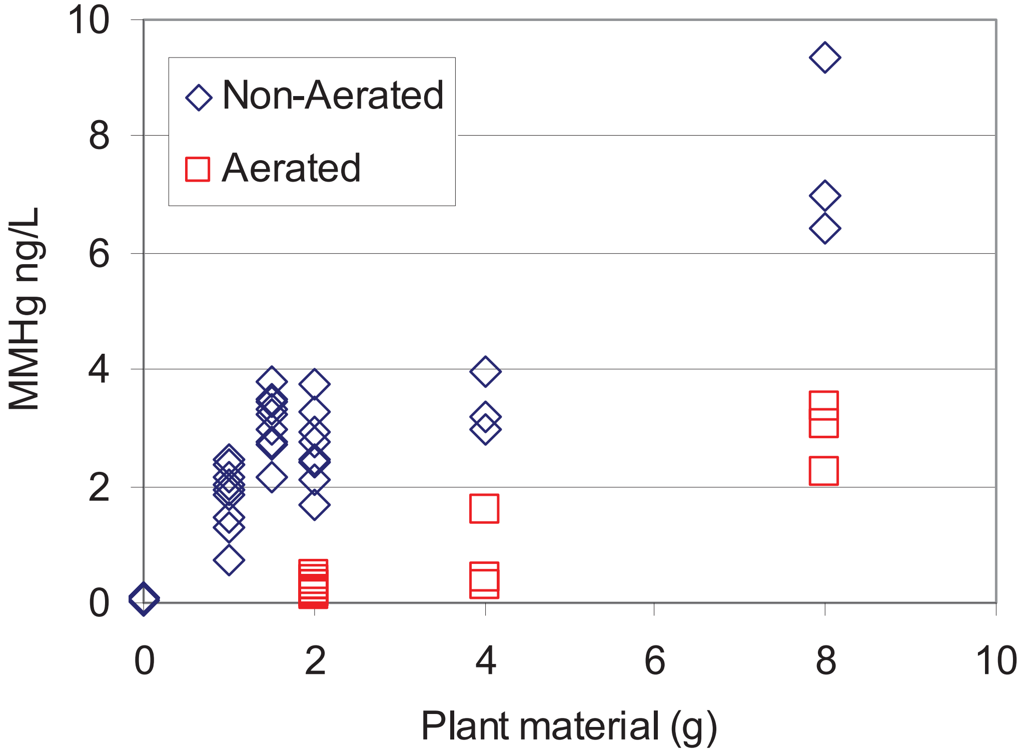


Figure 20. Methylmercury (MeHg) concentrations are shown for treatments of varying amounts of sediments and plant material under aerated (□) and non-aerated (◊) conditions.

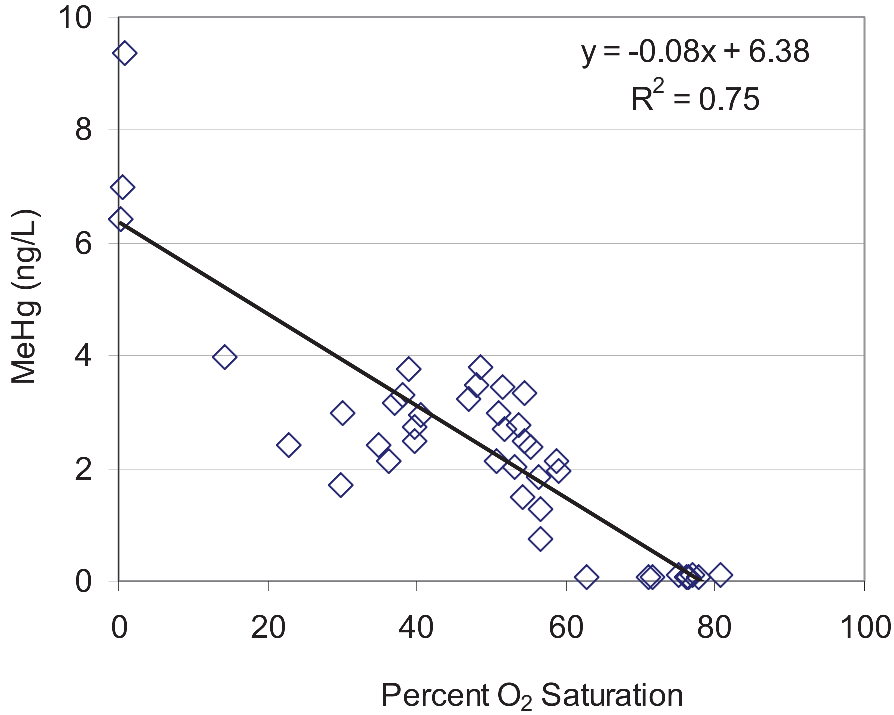


Figure 21. Relationship between methylmercury (MeHg) and percent oxygen (O_2) saturation for non-aerated treatments in experiment 2 was observed to be significant.

Appendix F: Dissolved Organic Matter

Strategy for Resolving MeHg and Low Dissolved Oxygen Events in Northern Suisun Marsh

(SWRCB AGREEMENT # 06-283-552-0)
Association of Bay Area Governments

July 2010

Prepared By:

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Introduction

The San Francisco Estuary is the largest estuary on the west coast, containing over one thousand miles of waterways and multiple habitat types, including wetlands and marshes. Suisun Marsh is located within the San Francisco Estuary downstream from the Sacramento-San Joaquin River Delta and upstream from the Central San Francisco Bay. With about 30,000 acres of sloughs and small bays, about 52,000 acres of managed wetlands, and about 6,300 acres of unmanaged tidal marsh, Suisun Marsh is the largest contiguous brackish water wetland in California. In addition to providing excellent habitat for wildlife, wetlands create the ideal biogeochemical conditions for increasing the toxicity of mercury (Hg); in the presence of inorganic Hg wetland habitat sets up the ideal conditions for the conversion of Hg to its more toxic organic form methylmercury (MeHg) (St. Louis, Rudd et al. 1994; Hurley, Benoit et al. 1995; Rudd 1995; St. Louis, Rudd et al. 1996).

In the managed wetlands, maintaining low soil salinities is a high priority. If the soils become too salty, salt tolerant plants are encouraged to invade which provide less value to wildlife than fresh water wetland plants. While the wetlands are flooded for migratory waterfowl use, water is circulated throughout the club to keep salinities as low as possible. In the winter and early spring, following waterfowl hunting season, a series of 2-3 flood-drain cycles are usually performed to flush accumulated salts from the soils, taking advantage of reduced water salinity in Suisun Marsh during that time of year. In the summer, the wetlands are normally drained for a period of 1-3 months so that landowners can perform other maintenance activities on the wetlands. This dry period also allows wetland plants to seed and sprout. The entire years work, leaching, circulating, mowing, disking, and other maintenance is done so that the wetland plants will provide food, in the form of seed, and cover not only for waterfowl and other wildlife but also for aquatic inverts which are also used as a food source.

Severely low dissolved oxygen (DO) events resulting from environmental conditions and management actions in some managed wetlands adversely impact the aquatic ecosystem of various sloughs in Suisun Marsh. Peytonia, Boynton, and Suisun Sloughs in the northwest Marsh have exhibited the most significant low DO problems. Most managed wetlands are dry during the summer and early fall months when land managers carry out maintenance activities. Fall flood-up typically involves a series of one or more flood-drain-flood cycles after which the wetlands circulate water through the winter and drain at variable times in the spring depending on particular property management objectives. The fall flood-up cycle can create low DO waters that upon release send low DO plumes into receiving waters (tidal sloughs) impacting aquatic organisms, including killing at-risk fish species and impairing valuable fish nursery habitat. Other contributions to low DO in Suisun Marsh are likely, such as nutrient loading that stimulates aquatic productivity and the resulting biological oxygen demand from decomposition of organic matter.

Coincident with low DO events, are a mixture of biogeochemical conditions leading to elevated MeHg concentrations. MeHg is a neurotoxin that transfers up the food chain through bioaccumulation and adversely effects fish and wildlife species and poses a health risk to humans. MeHg is thought to be produced in association with bacterial sulfate reduction, a process favorable in low DO environments in the presence of a labile form of inorganic mercury. The amount of MeHg released from managed ponds is currently unknown; preliminary data indicate marsh releases have elevated MeHg concentrations that may range up to an order of magnitude over accepted limits. Marsh drainage is typically rich in dissolved organic matter (DOM) that stimulates microbial activity increasing the biological oxygen demand (BOD) in surrounding waters. It is has long been recognized that species of mercury in the water column and sediments are interrelated to DOM. The amount and structural characteristics of DOM influence mercury biogeochemical cycling by impacting methylation, volatilization, and bioavailability. In addition, recent studies have shown that dissolved mercury in surface waters is associated with DOM, and that this relationship is influenced by DOM composition (Lamborg et al. 2003; Yoon et al. 2005; Skyllberg et al. 2006; Schuster et al. 2008).

Effective management strategies for mitigating low DO and high MeHg concentrations in managed wetlands require understanding of the biogeochemical factors affecting these consituents. The overarching goal of this study was to implement and evaluate the effectiveness of one or more management strategies to reduce the production of low DO events associated with managed wetlands operations (e.g. flooding, mowing, discing, chemical treatment). In addition, it is likely the reduction of low DO events will result in a decrease in MeHg concentrations within wetland ponds and reduce MeHg loading to surrounding marshes as conditions will be less favorable for MeHg production. The aim of this report is to identify relationships and trends between wetland treatment strategies and hydrology (e.g. channel vs interior sites) to source contributors to BOD, such as DOM and vegetation. By examining how DOM amount and quality differs temporally and due to wetland location (ditch, channel, interior and wastewater outflow sites), preflood treatment, and vegetation control (discing, mowing, chemical treatment), we can gain insight into the sources and reactivity of the bulk DOM pool. Both DOM concentration and composition can also be related to DO and mercury concentrations to elucidate the relationships among these parameters.

Optical Properties Indicative of DOM Quality

Interaction of a filtered water sample with light is determined both by DOM amount and composition and thus measurement of optical properties provides quantitative and qualitative information about the DOM pool. For absorbance data, SUVA – UV absorbance normalized to

DOC concentration – is often used as a proxy for aromatic content (Weishaar et al. 2003). The exponential shape of the absorbance curve – the spectral slope (*S*) – has been shown to relate to DOM aromatic content and molecular weight; decreasing *S* is associated with higher aromatic content and increasing molecular weight (Helms et al., 2008; Spencer et al., 2009). Similarly, fluorescence data has been shown to provide information about DOM character and origin. The fluorescence index (FI) – the ratio of two fluorescence wavelengths – has been widely used to indicate relative contributions of algal versus terrestrial derived DOM; higher FI are associated with algal derived material which has lower aromatic content and lower molecular weight, while lower FI values are associated with more highly processed, terrestrial derived material that has greater aromatic content and higher molecular weight (McKnight et al., 2001; Jaffe et al., 2008).

Further, qualitative information can be derived from the identification of peaks in the excitation-emission matrix (EEM) spectra reflective of different DOM pools such as humic and fulvic acids (Peaks A and C), and protein-like material (Peak T) using factor analysis techniques (Stedmon et al., 2003; Coble, 2007; Hudson et al., 2007). The application of parallel factor analysis (PARAFAC) is used to identify different classes of DOM which make up the entire EEMs spectra, and the relative proportions of these components can reveal both quantitative and qualitative differences between samples (Jaffe et al., 2008; Stedmon and Bro, 2008; Cook et al., 2009).

Methods and Materials

Study Area Description

Suisun Marsh is located near the center of the San Francisco Estuary in Solano County, California. Suisun Marsh is the largest brackish water tidal marsh (ca. 116,000 ac) on the Pacific Coast of the United States. Its brackish conditions result from the mixing of freshwater inputs from California's two major rivers – the Sacramento and San Joaquin – whose confluence lies immediately to the east, with saltwater inputs arriving with the semi-diurnal tides through the Golden Gate to open waters of Honker and Suisun Bay. Suisun Marsh accounts for over 10% of California's remaining wetlands, including approximately 52,000 acres of managed wetlands, 27,700 acres of upland grasses, 6,300 acres of tidal wetlands, and 30,000 acres of bays and sloughs (IEP 2007). The Marsh provides habitat for thousands of waterfowl migrating in the Pacific Flyway and supports over 221 bird species, 45 animal species, more than 40 fish species and 16 different reptilian and amphibian species (IEP 2007).

The study design was focused on two managed wetlands in Suisun Marsh – Club 112 and 123 – which are hydrologically connected to Peytonia and Boynton Sloughs. The managed wetlands share a common flood/drain supply channel system with straightforward hydrology, allowing monitoring and identification of water quality parameters under comparatively controlled conditions.

Discrete sampling

Surface water grab samples were collected directly into acid washed amber glass sample bottles. Samples were kept on ice and transported to the organic chemistry laboratory at the USGS California Water Science Center in Sacramento, CA, and subsequently refrigerated at 4^{o}C. On arrival, samples were filtered through pre-combusted glass-fiber filters, using 47 mm, 0.3 µm nominal pore size GF/F filters that had been baked at 500 deg C to remove residual organic materials. Samples were analyzed for dissolved organic carbon (DOC), absorbance, and fluorescence. Samples for DOC, absorbance and fluorescence were analyzed within 5 days of collection. Samples for DOC concentration were acidified to pH 2 using reagent grade concentrated HCl immediately after filtration.

DOC Concentration

DOC concentration was measured using high temperature catalytic oxidation with a Shimadzu TOC-V CSH total organic carbon analyzer measuring non-purgeable organic carbon (Bird et al., 2003). The method uses high temperature catalytic oxidation to oxidize the organic carbon to CO_2, with a non-dispersive infrared detector to measure the CO_2. The mean of three to five injections was calculated for every sample and precision, described as a coefficient of variance (CV), was <2% for the replicate injections.

Absorbance

A Cary model 300 photometer (Varian, Palo Alto, CA) with a 1-cm-pathlength cuvette was used to measure absorbance of discrete water samples. Absorbance was measured over ultraviolet and visible wavelengths (200–800 nm) with 1-nm resolution. Cuvettes were cleaned using an acid-base treatment and rinsed thoroughly with organic-free water before use. Degassed, organic-free water blanks were run before and after every five measurements, with acceptable blanks (<0.005 AU) subtracted from sample measurements. Samples were equilibrated to 25 deg C before analysis. Specific UVA (SUVA), a proxy for aromaticity, was calculated by dividing absorbance at 254 nm by DOC concentration, and is reported in the units of L mg C^{-1} m^{-1} (Weishaar et al., 2003). The spectral slope coefficient (*S*), was calculated using a non-linear spectral fit of an exponential function with a baseline offset correction (Markager and Vincent, 2000) to the absorption spectrum in the range of 275-295 nm using the fminsearch function in MATLAB:

$$a_g(\lambda) = a_g(\lambda a_g) \exp[-S(\lambda - \lambda_{ref})] + K \qquad (1)$$

where $a_g(\lambda)$ is the absorption coefficient of CDOM at a specified wavelength, λ_{ref} is a reference wavelength, S is the slope fitting parameter (coefficient) and K is the offset correction, both calculated using an unconstrained nonlinear optimization technique (*fminsearch)* in MATLAB (MATLAB, Inc. 2008). Absorbance spectra was fitted using an exponential fit (e.g. Blough and Del Vecchio 2002; Babin et al., 2003, Twardowski et al. 2004) and a spectrally fitted offset, K, as an alternative to offset correction methods (e.g. Bricaud et al, 1981), using subtraction of absorption in the red (see discussion section below). Spectral slope ($S_{275\text{-}295}$) of the absorbance curve has been shown to relate to DOM aromatic content and molecular weight; decreasing $S_{275\text{-}295}$ is associated with higher aromatic content and increasing molecular weight (Blough and Del Vecchio, 2002).

Fluorescence

Fluorescence excitation-emission matrices (EEMs) were measured with a SPEX Fluoromax-4 spectrofluorometer (Horiba Jobin Yvon, NJ, USA) using a 150 watt Xenon lamp. Fluorescence intensity was measured at excitation wavelengths of 240 to 440 nm at 10 nm intervals, and emission wavelengths of 290 to 600 at 5 nm intervals on samples equilibrated to room temperature (25°C) in a 1 cm quartz cell. Daily excitation and emission verifications were completed by inspecting lamp and water-Raman spectra per the manufacturer's specifications and suggestions. EEMs were blank corrected in MATLAB to remove Raman scattering and normalized to the daily water Raman peak area; Rayleigh scatter lines were removed after blank correction. Instrument bias was corrected using manufacturers supplied excitation and emission correction factors. Inner filter corrections were applied to samples with absorbance at 254 nm (UVA_{254}) greater than 0.03 (1 cm cuvette or 6.9 m^{-1}) as described by MacDonald et al. (1997).

The fluorescence index (FI), a calculation of the ratio of emission intensities at 470 nm to 520 nm at an excitation of 370 nm, was used to differentiate DOM contributions from algal versus terrestrial sources (McKnight et al., 2001; Jaffe et al., 2008). The humification index (HIX), used to determine the extent of humification by quantifying the amount of EEMs shifting toward longer wavelengths as humification increases, was calculated as follows:

$$HIX = \Sigma I_{435\text{-}480}/(\Sigma I_{300\text{-}345} + \Sigma I_{435\text{-}480}) \qquad (2)$$

Statistical Analyses-PARAFAC

Corrected EEMs were analyzed using Parallel Factor Analysis (PARAFAC), a type of three-way principle components analysis (PCA) that resolves absorption and emission spectra of orthogonal fluorophore groups (components) and determines loadings (proportional to concentrations) of each component. The algorithm assumes that the fluorescence intensity at any excitation/emission pair ($I_{ex,em}$) within the EEM is a linear sum of the product of concentration loading (*L*), absorption (*A*), and quantum efficiency (*v*) of each component *i* at each absorption/emission pair:

$$I_{ex,em} = \sum_{i}^{N} L_i A_i v_i \tag{3}$$

PARAFAC resolves EEMs into trilinear components characterized by unique excitation and emission curves and determines the loadings of each component proportional to concentration (Anderson and Bro, 2000). PARAFAC modeling was conducted using MATLAB script to assemble EEMs model input data, execute the PARAFAC model, model figures and results. Goodness of fit was determined by visual inspection of the measured, modeled and residuals (measured minus modeled) EEM spectra, as well as by good agreement between duplicates. PARAFAC models were validated using a combination of (1) outlier identification, (2) residual analysis, (3) component validation and (4) replication by split half analysis (Stedmon, 2008)

Principle Components Analysis

In this study, PCA was used primarily as an exploratory tool for data analysis, to reduce the dimensionality of the physicochemical and optical properties to lower dimensions and to detect structure in the relationships between each variable (The Unscrambler, version 9.2, Camo Technologies, Oslo, Norway). The purpose of PCA is to derive a small number of independent linear combinations or principal components (PC) of a set of variables that retain as much of the information in the original variables as possible. Each resulting PC is a linear combination of the original measured variables which are uncorrelated and ordered such that the first few PC's explain most of the variation in the original variables. The first component (PC_1), accounts for the maximum of the total variation while the second component (PC_2), uncorrelated with PC_1, accounts for the maximum variation of the residual variance and each successive PC until the total variance is accounted for.

Model validation consisted of full cross validation where every sample was used for both the model prediction and testing by omitting a sample from the calibration data set and calibrating the model on the remaining sample attributes. Model values for the omitted samples were predicted and prediction residuals computed successively with another subset of the calibration set v until every attribute has been left out once. Model prediction residuals are combined to compute the validation residual variance and RMS error of prediction.

Statistical Analyses

To determine whether there were significant differences in DOM amount and quality by date or by management action, we applied a general linear model (Proc GLM) using, as appropriate, the following factors as main effects: (1) study year (2) Club, (3) time since flood-up, (3) landscape position, (3) management setting.

RESULTS

DOC Concentration

DOC concentrations varied widely from 3 to 100 mg/L, with the highest DOC concentrations measured during drawdown in Club 123 in September 2008 (Figure 1). DOC concentrations, particularly in Club 112, were higher during the earlier weeks after flooding, dropped over time and seemed to stabilize after approximately 5 weeks of flooding. Within both wetlands, sites representing waste water inflows (112-3, 123-6 and 123-7) had significantly lower DOC concentrations compared to other sites. No clear differences were found in DOC concentration between channel and interior wetland sites, however ditch sites had lower concentrations than these sites within the wetlands. Taking into account time since flood-up and landscape position, there were no statistical differences in DOC concentration between clubs or management setting.

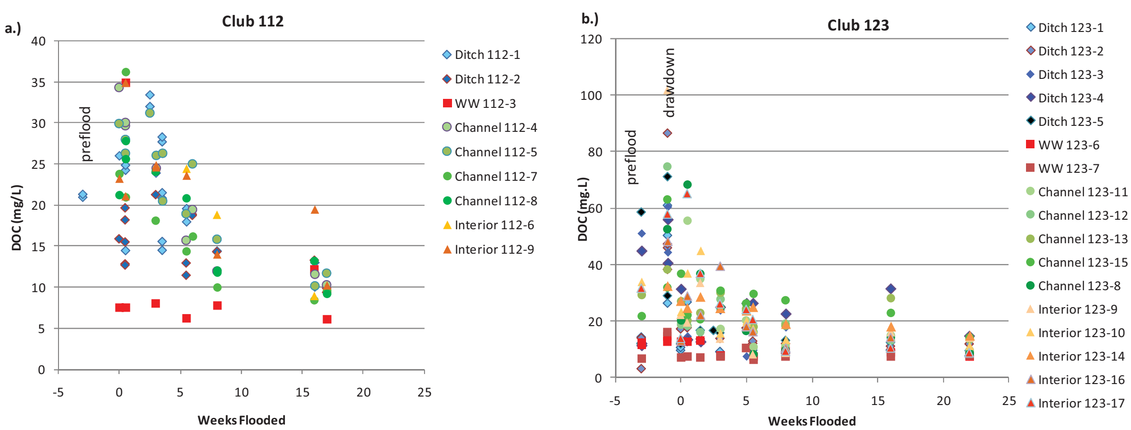


Figure 1: Dissolved organic carbon (DOC) concentrations by site for both years of sampling plotted against weeks since flooding for a) Club 112 and b) Club 123. Negative weeks represent pre-flood and drawdown, as indicated.

DOM Composition

SUVA and Spectral Slope

Comparison of SUVA and S values reveal differences in bulk DOM composition; higher SUVA and lower S values are associated with greater aromatic content and molecular weight, while lower SUVA and higher S values are associated with lower aromatic content and molecular weight (Helms et al., 2008). As was seen with DOC concentration, the range of SUVA values for Club 123 were both wider and greater than Club 112; the majority of samples from Club 112 had SUVA values between 2 and 3 L mg C^{-1} m^{-1}, while many samples from Club

123 had SUVA values above 3 L mg C^{-1} m^{-1} (Figure 2). SUVA values were elevated during the drawdown, suggesting that release of DOM from soils and degraded plant material was the predominant source of this material. Bulk DOM from fresh plant and algal sources has lower aromatic content compared to more degraded DOM. In both Clubs, SUVA values were generally low for sample sites influenced by waste water, which reflects the presence of more labile DOM with lower aromatic content.

In Club 123, there was a notable increase in SUVA values after the first few weeks of flooding. This increase could indicate the consumption of more labile DOM and/or production of more highly processed DOM with higher aromatic content. By March, week 22 following flood-up during the first year of sampling, SUVA values declined in Club 123, which may reflect the release of DOM with lower aromatic content from growing vegetation and/or algae, or may also reflect hydrologic flushing of wetland derived DOM and replacement with a new pool of DOM by inflow waters.

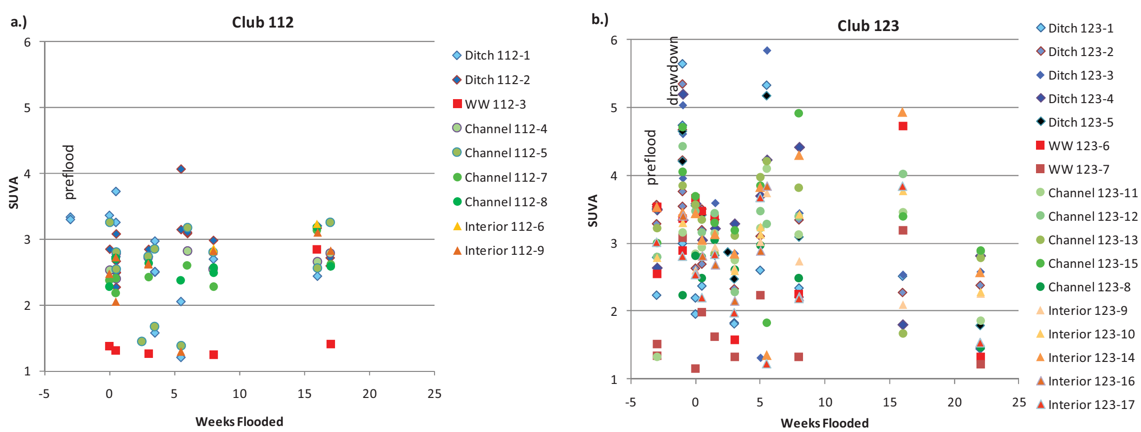


Figure 2: Specific UVA (SUVA) values by site for both years of sampling plotted against weeks since flooding for a) Club 112 and b) Club 123. Negative weeks represent pre-flood and drawdown, as indicated.

The range of spectral slope coefficients (*S*) in this study fall within ranges commonly found in the literature (0.010 – 0.020 m^{-1}) and are representative of DOM cycling in estuaries. The lowest *S* values were seen during drawdown in Club 123, which like the elevated SUVA values suggests release of higher molecular weight, aromatic DOM from degraded organic matter during that period (Figure 3). In Club 123, *S* coefficients were on average higher during the first few weeks of flooding and then decreased in subsequent weeks. This again may indicate fresh, labile DOM present in the early stages of flooding was converted to more refractory DOM as the period of flooding continued. Previous work (e.g. Gao and Zepp, 1998; Helms et al., 2008) has also shown that photoexposure leads to an increase in *S* values, and so it is possible that photolytic processes occurring during flooding lead the increases in S values seen over time in Club 112 with increasing flood time, as well as at week 22 in Club 123. As mentioned above, the increase in S values for samples collected during week 22 in Club 123 may also reflect production of lower molecular weight, labile DOM or flushing out of wetland derived DOM by inflow waters.

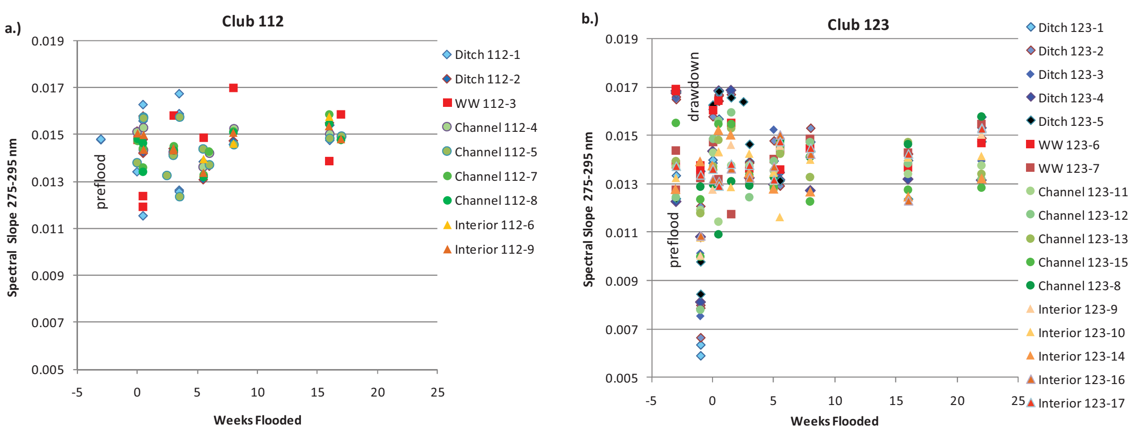


Figure 3: Spectral Slope values by site for both years of sampling plotted against weeks since flooding for a) Club 112 and b) Club 123. Negative weeks represent pre-flood and drawdown, as indicated.

Fluorescence Index

The fluorescence index (FI) has been widely used to indicate relative contributions of algal versus terrestrial derived DOM; algal derived material which has lower aromatic content and lower molecular weight is associated with higher FI values, while more highly processed, terrestrial derived material that has greater aromatic content and higher molecular weight is associated with lower FI values (McKnight et al., 2001; Jaffe et al., 2008). FI values in this study ranged between 1.2 and 2.0, indicating there were significant changes in DOM composition and source among samples (Figure 4). Most notably, FI values were highest in waste water influenced sites (~1.9), which is commonly reported (Hudson et al., 2007). The increase in FI values in Club 123 at week 22 (March 2008) supports the hypothesis there was significant contributions of DOM from algal production or leached from vegetation growing in the wetland. This shift could be due to production within the wetland, as well as due to the inflow and exchange of water from outside sources.

The high FI values associated with site 123-1 indicates that this ditch location was influenced by waste water inflow during most of the sampling periods.

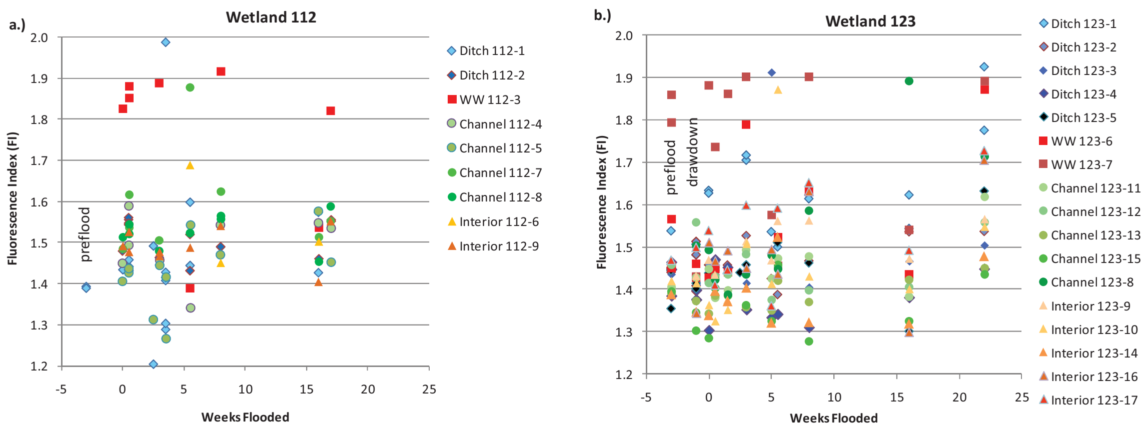


Figure 4: Fluorescence Index (FI) by site for both years of sampling plotted against weeks since flooding for a) Club 112 and b) Club 123. Negative weeks represent pre-flood and drawdown, as indicated.

Comparison of SUVA and FI values for club 112 and club 123 reveal a strong relationship between absorbance and fluorescence data, where higher SUVA values are indicative of lower FI (Figure 5).

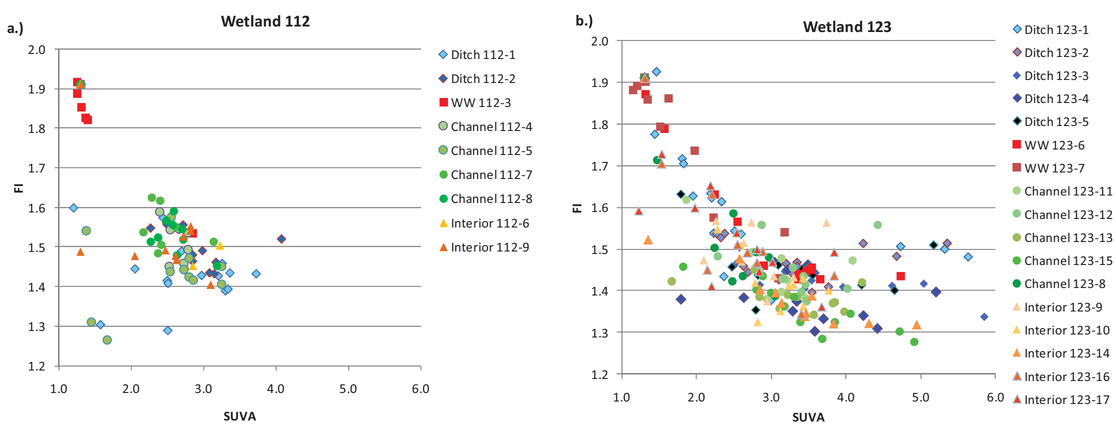


Figure 5: SUVA values plotted against Fluorescence Index values for Club 112 (a) and Club 123 (b). Data reveals a strong relationship between absorbance and fluorescence data; higher SUVA values lower FI.

Dissolved Oxygen Concentrations

Dissolved oxygen (DO) concentrations were available for a subset of the grab samples, predominantly in Club 123 (Figure 6). There was a wide range of DO concentrations (0.1-12 mg/L). During the drawdown period, DO concentrations were particularly low (<1 mg/L) for all sites with the exception of the waste water influenced sites. Although there was not a significant correlation between DOC and DO concentrations, DO was consistently low in water with high concentrations of DOC; at DOC concentrations exceeding 40 mg/L, DO concentrations were generally less than 1 mg/L (Figure 6B). During the flooded period, the two sites representing waste water inflows generally had high DO concentrations, channel sites generally had low DO concentrations (<3 mg/L), while ditches and interior sites had a wide range of DO concentrations. Based on this limited data set there was no clear trend in DO concentration with time since flooding, nor any significant differences by management treatment.

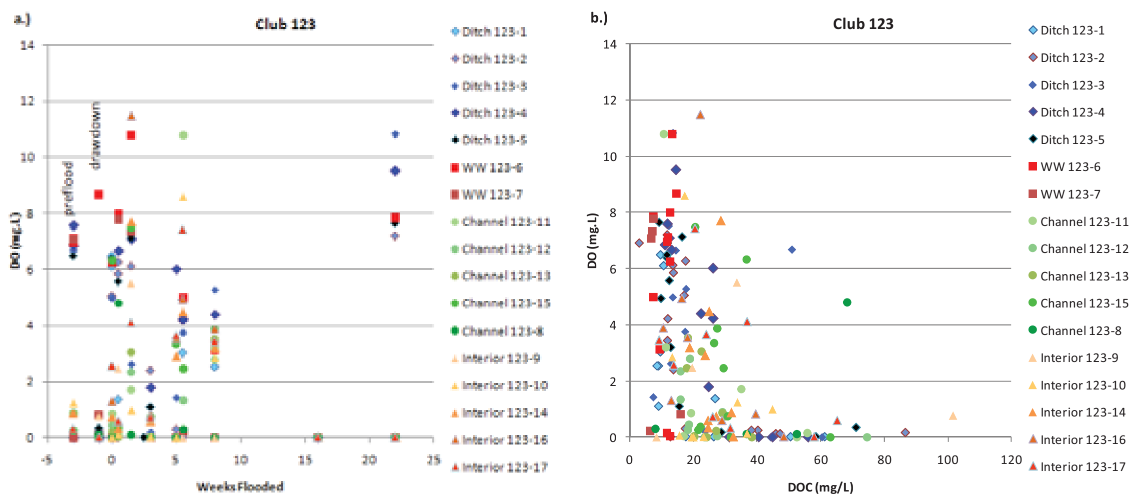


Figure 6: Dissolved oxygen (DO, mg/L) values by site for both years of sampling for Club 123 plotted against a.) weeks since flooding and b.) DOC concentration. Negative weeks represent pre-flood and drawdown, as indicated.

PARAFAC Analysis

The application of PARAFAC was used to identify different classes of organic matter present within the EEMs spectra. PARAFAC resolves EEMs into trilinear components (concentration, excitation and emission loadings) characterized by unique excitation and emission curves. PARAFAC determines the loadings of each component which are proportional to concentration. The relative proportions of these components can reveal qualitative differences between samples (e.g. Stedmon et al., 2003; Cory and McKnight 2005; Murphy et al., 2008; Stedmon and Bro, 2008; Jaffe et al., 2008).

PARAFAC identified 4 model components that best represented the variability of the combined sample EEMs. Validation of the modeled EEMs included analysis of the model residual EEMs (measured – modeled) where residual EEMs appear to contain little remnant signal information, thus adequately describing the fluorescent DOM in each sample of the data set (Figure 7). Validation of the modeled components was also accomplished by comparing the spectral shape of the components derived by the models. The excitation and emission spectra of the modeled components are representative of modeled EEMs from a variety of studies and lab experiments in natural waters: humic-like and fulvic-like DOM (Peaks A and C) and tryptophan or waste water influenced DOM (Peak T, Figure 8). The weight percent distribution of the model components were compared to sample date and site characteristics (channel, interior, waste water influenced) to confirm that modeled components were reflective of sample site characteristics.

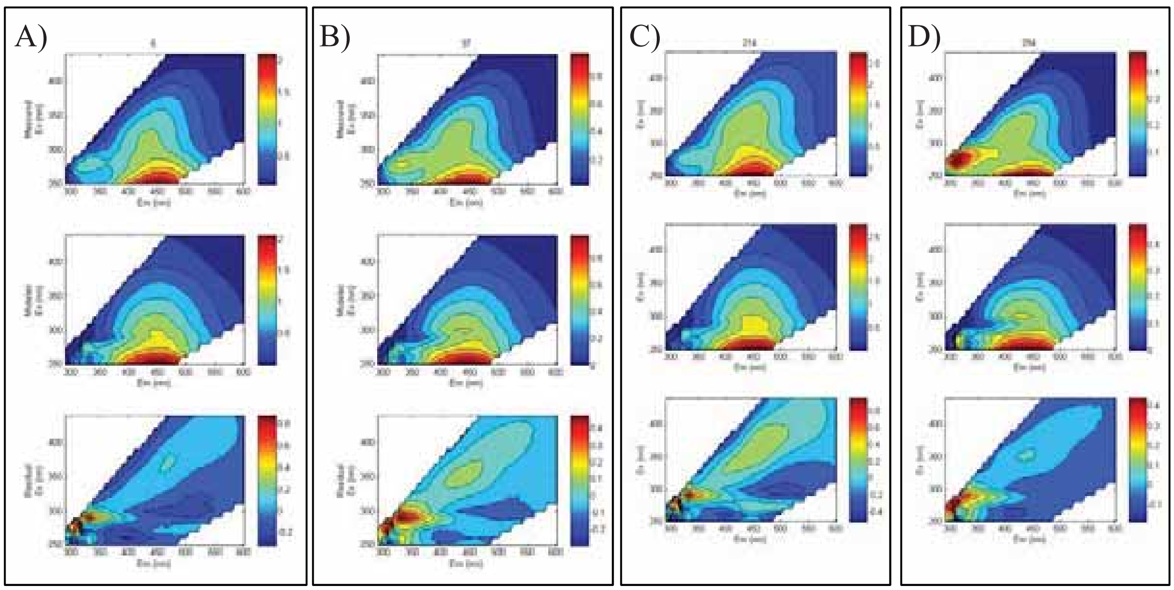
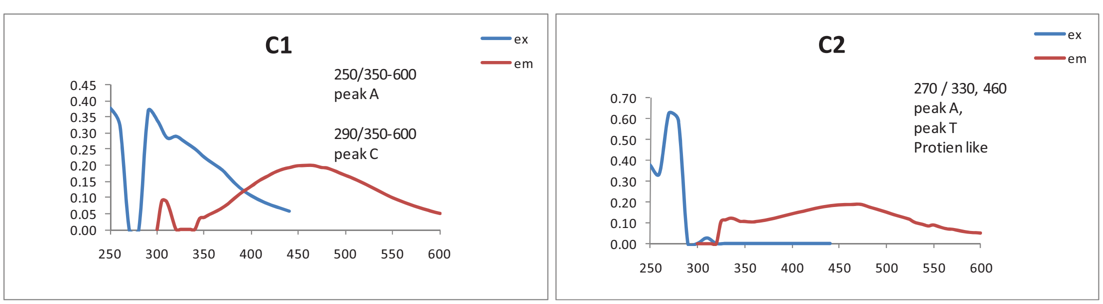
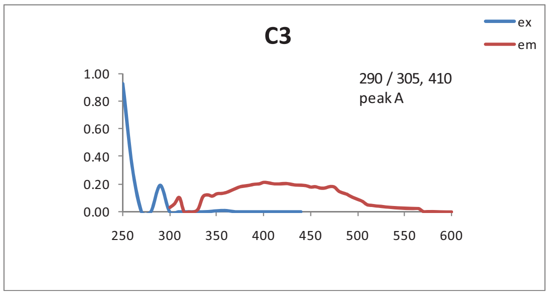


Figure 7: Examples of PARAFAC modeled results showing from top to bottom; measured EEMs, PARAFAC modeled EEMs, and residual EEMs (modeled EEMs subtracted from measured EEMs) for sites 123-6 a waste water influenced site adjacent to a well defined channel (frames A&B). Frames C&D show results from 112-7, an interior wetland sampling site, not influenced by waste water or channel flow.





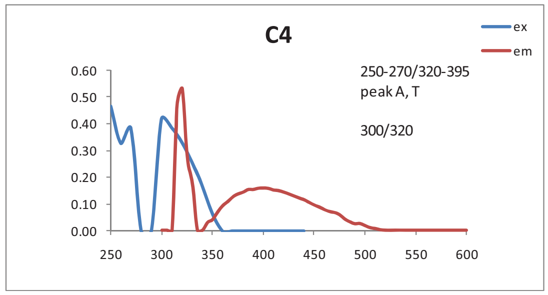


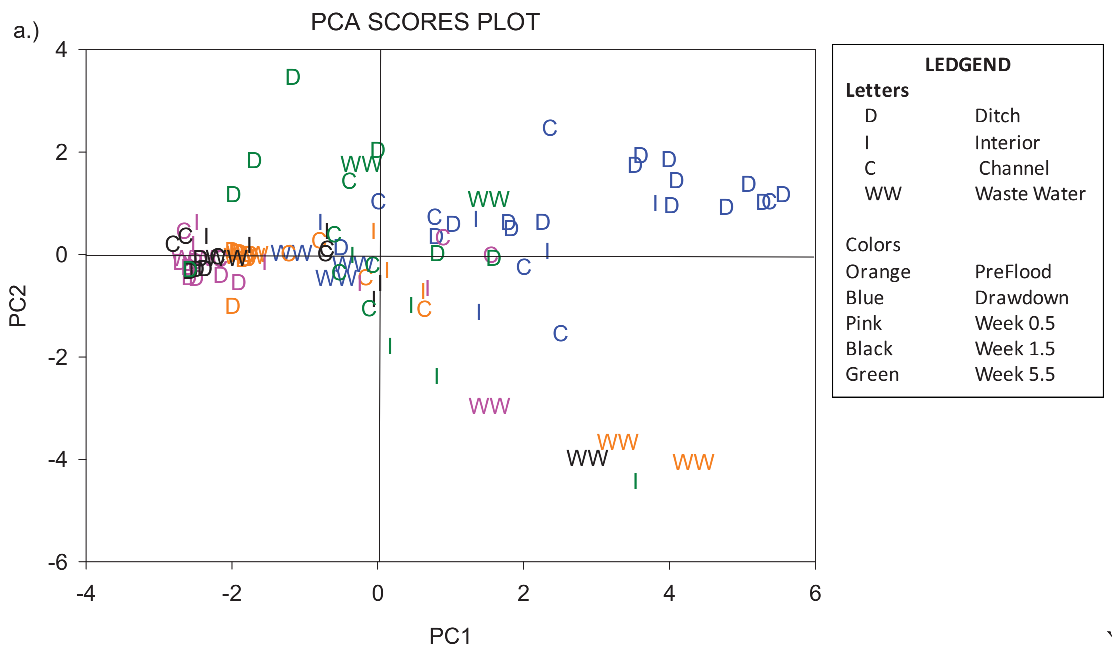
Figure 8: Excitation (blue) and emission (red) curves for the four PARAFAC modeled components identified in the total data set.

Exploratory analysis using PCA

Principal component analysis (PCA) was used to detect patterns in the data set and to visualize the information present in the qualitative data obtained from optical properties. Shown in Figure 8 is PCA output for a model consisting of 8 DOM qualitative parameters (SUVA, FI, S, HI, %C1, %C2, %C3 and %C4) for samples collected in Year 2 of the study from Club 123. The first and second principal components accounted for 83% of the variance. Principal Component 1 (PC1, X-axis in Figure 8), represents variation in humic content: on the positive scale is DOM associated with protein-like fluorescence Peak T and on the negative scale is DOM associated with more humic- and fulvic-like fluorescence Peaks A and C as well as higher values for the Humic Index (HI) and Spectrial Slope (*S*). Principal Component 2 (PC2, Y-axis) discriminated more between DOM source: on the positive scale is material with high SUVA and low FI values associated with higher molecular weight, aromatic terrestrial derived material while the negative scale is associated with low SUVA high FI values associated with more labile material.

The PCA results illustrate that samples collected during the drawdown not only had higher DOC concentrations than other samples, but that DOM quality notably differed (Figure 8). Drawdown samples from ditch sites in particular were associated with higher PC1 and PC2 scores; this suggests that although DOM flushed out of the ditch sites had higher molecular weight and aromatic content associated with terrestrial derived material, this DOM pool also contained a significant amount of more labile, protein-like DOM associated with Peak T fluorescence.

Results from this PCA analysis also showed that DOM quality in ditches sampled during the pre-flood and immediately following the flood-up (October, 2008) had higher humic content and molecular weight compared to other sampling dates (low PC1 scores). Several of the sites located near the wastewater outflows were also clearly distinguishable due to their high FI and higher percentage of protein-like Peak T (%C4) fluorescence with is typical for waste water effluent.



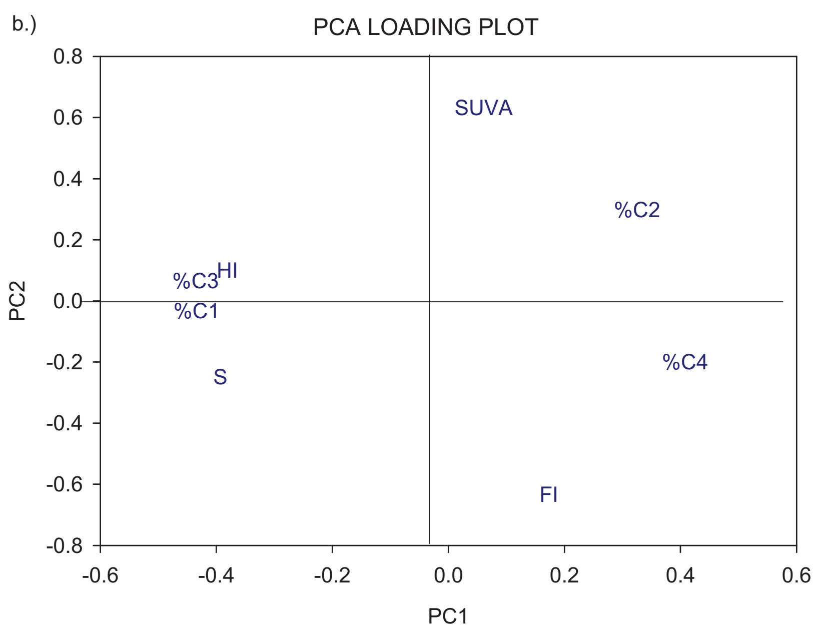
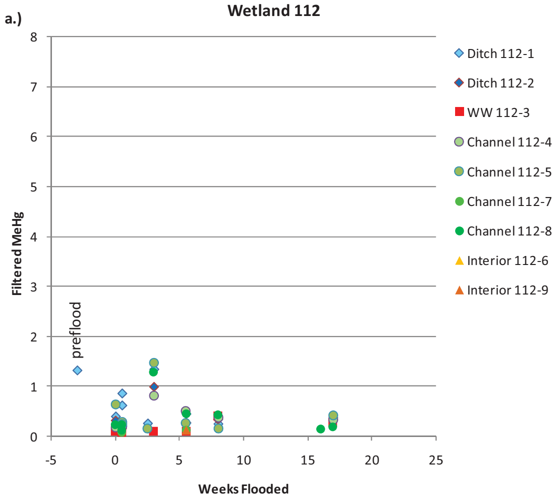


Figure 9: Principal Component Analysis (PCA) scores plot (A) and loading plot (B) run on Club 123 2008 data using 8 qualitative DOM parameters. In figure A, letters indicate landscape position - D for ditch, C for Channel, I for Interior, and WW for waste water sites – while color indicates week relative to flood.

DOC Concentration vs. Dissolved MeHg Concentration

There was no statistically significant relationship between DOC concentration and MeHg concentrations (Figure 11). However, almost all samples containing elevated concentrations of MeHg (>1 ng/L) also had elevated concentrations of DOC (> 20 mg/L).



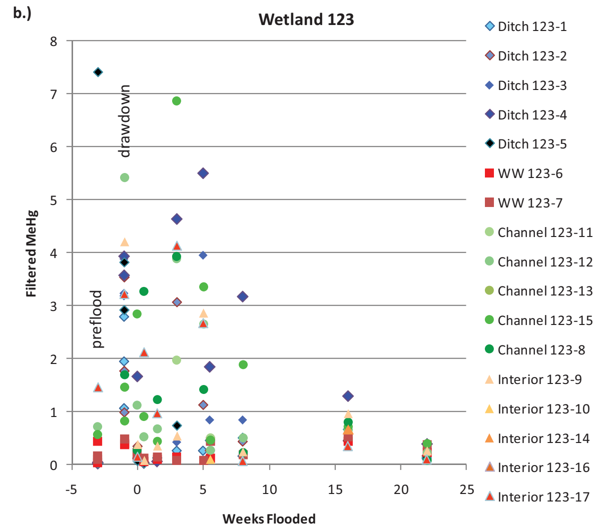
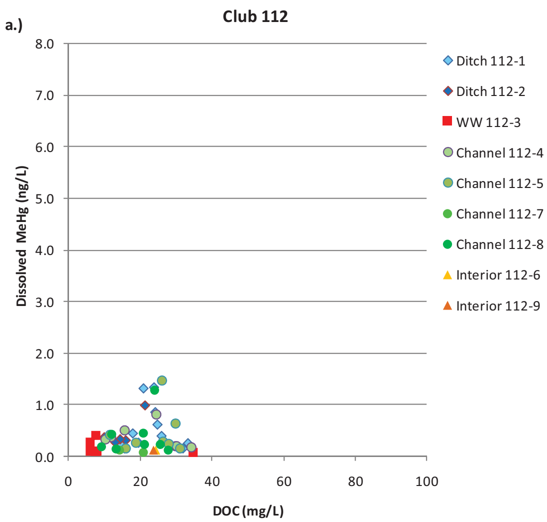


Figure 10: Filtered methyl mercury (MeHg) concentrations by site for both years of sampling plotted against weeks since flooding for a) Club 112 and b) Club 123. Negative weeks represent pre-flood and drawdown, as indicated.



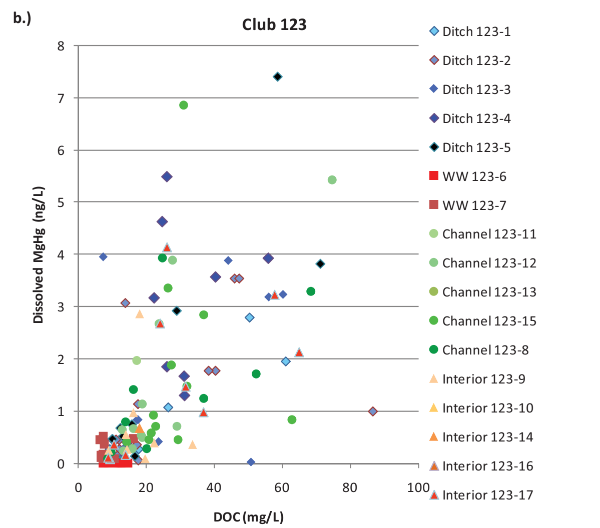


Figure 11: Relationship between DOC concentration and dissolved MeHg concentrations for (A) Club 112 and (B) Club 123. Data shown includes both years of sampling.

Discussion

Both the concentration and quality of DOM affects biogeochemical cycling. By examining changes in the DOM pool, inferences can be made about the source and reactivity of this material.

DOC concentrations varied significantly among the samples collected in this study. Most notably, DOC concentrations at wastewater inflow sites in both clubs 112 and 123 were as much as a 4 times lower than concentrations measured in ditch, channel and interior locations (Figure X). Waste water inflows also had high DO and low MeHg concentrations, suggesting that the main effect of these inflows is dilution and aeration of water within the wetlands. However, qualitative parameters indicate that DOM from these sites is comprised of lower molecular weight, lower aromatic containing DOM which likely increases biological oxygen demand (BOD) and thus may contribute to low DO conditions downstream of these sites.

Biological oxygen demand – a measure of oxygen required for decomposition of organic matter and/or oxidation of inorganic materials such as sulfide – is introduced into many surface water catchments via sources of organic matter such as sewage effluent, surface runoff, and natural biotic processes (Hemond and Benoit 1988). In addition to the addition of labile DOM from wastewater inflows, low DO concentrations in the interior and channel sites during the drawdown and after rewetting point towards sources of labile organic matter in the water column from a mixture of (1) soil organic matter, (2) macrophytes and (3) inflow waters.

Changes in DOM amount and character between the 2008 pre-flood sampling and drawdown sampling reveal that during this 1-week period there was a substantial increase in marsh water DOC concentration and a shift to much more aromatic DOM. There was also a concomitant decrease in DO concentration and increase in dissolved MeHg concentration, particularly at the ditch sites. The increase in DOC concentration over this short time frame must be attributed to release of DOM from degrading soil and plant organic matter. Microbial degradation of this DOM is likely responsible for the rapid depletion of DO, and a shift to more aromatic structures. Furthermore, DOM released from sediments likely brought both inorganic Hg and MeHg into the water column (Schuster et al. 2008).

Among all samples collected, the highest DOC concentrations were seen in the 2007 drawdown waters of Club 123, with high values ranging from 60 to 100 mg/L. DOM compositional parameters indicate that water in the drainage ditches during the drawdown differed from all other samples; despite relatively high SUVA values, fluorescence data suggests the presence of protein-like, labile material. Like most sites sampled during the drawdown with the exception of the wastewater influence sites, these ditch sites generally had low DO concentrations and high MeHg concentrations.

Following the October flood-up, DOC concentrations were similar between Club 112 compared to 123, despite differences in soil properties between these two wetlands. Soils of club 112 are characterized as a silty clay loam, compared to soils found in club 123 which are much more organic ranging from peaty muck to mucky clay. In contrast to concentration, there were significant differences in DOM quality between the two Clubs: taking into consideration weeks since flood up-and landscape position, overall Club 123 had higher values for SUVA, C1, C3, C4 and HI and lower values for FI and C2. This suggests that the DOM pool exiting Club 123 has a greater proportion of soil derived DOM. There is also evidence that Club 123 had lower DO and higher MeHg concentrations than Club 112. Based on available data, it is unclear whether the 2008 drawdown treatment in Club 123 had an impact on subsequent DOM dynamics.

In Club 112 there was a clear trend of decreasing DOC concentration over time following flood up, but in Club 123 this trend did not hold up for all sites. Results from PCA of the 2008 Club 123 DOM qualitative data reveal that DOM in water immediately following the flood up had a relatively high humic content. As time since flood up increased, there was a shift in DOM character which may reflect (1) processing of DOM within the wetland, (2) production of new DOM within the wetland, and/or (3) the hydrologic exchange of DOM present in the wetland by DOM entering the wetland in inflow waters. Changes in qualitative properties within the wetland following flood-up suggest degradation of the labile DOM pool lead to consumption of DO and the production of more recalcitrant DOM. However, in Club 123 during Year 1 of the study, by March (22 weeks after flood-up) DOM concentrations had decreased to about 10 mg/L and compositional parameters shifted to lower SUVA, higher S and higher FI values indicative of the addition of less humified, lower aromatic, lower molecular weight algal derived material. In addition, by this time DO concentrations were higher and MeHg concentrations lower throughout Club 123. It seems likely that this shift was largely due to hydrologic exchange, however changes in DOM composition could also be attributed to the addition of plant and algal derived DOM produced within the wetland as temperatures increased in the spring.

Changes in DOM are due to the leaching of marsh macrophytes and soil organic matter (SOM) into the water column after rewetting with the simultaneous transformation and loss of this material due to microbial degradation is likely occurring. Submersed biomass, both living and dead, (macrophytes) are often significant sources of DOM and nutrients in open water habitats as they exude soluble compounds and release them upon decay (Aiken, 1996). Further, organic matter originating in littoral zones of estuaries have been found to significantly influence aquatic metabolism in a number of estuarine studies (Moran et al., 2000, Fleck et al., 2004). \

Changes in vegetation management would be expected to influence the amount and rate of DOM released into the water column from macrophyte sources. In this data set, however, differences in DOC concentration *and quality* due to site management and vegetation differences were not apparent.

Conclusions

- Results of this study point to a mixture of terrestrially derived end-members—soil organic matter, vascular plants and waste water DOM—as primary sources of labile carbon to the wetlands studies.
- Changes in DOM amount and quality indicate that labile DOM is consumed in the first few weeks of flooding as biological and photochemical processes take place.
- Based on available data, there was no clear affect of wetland management (e.g. preflood/drain, mowing, discing, chemical treatment) on subsequent DOM concentration and quality.
- Drawdown water released from the pre-flood period contained high concentrations of DOC, MeHg, and low DO concentrations. Unless a clear benefit is found from this treatment, release of drawdown waters into neighboring sloughs will likely have an overall negative impact.
- Waters containing DOC concentrations above 40 mg/L generally had also had high concentrations of dissolved MeHg and low concentrations of DO, suggesting a link between these constituents.

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Appendix G: Hydrodynamics

Description of hydrodynamics and transport processes in Boynton and Peytonia Sloughs, Suisun Marsh, California

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Draft Technical Appendix Version 4-1-10

Abstract

Velocity and multi-parameter scalar sensors were deployed near the mouths of Boynton and Peytonia Sloughs in Suisun Marsh, near Fairfield California. Suisun Marsh comprises over 100k acres in the brackish portion of the northern reach of the San Francisco Estuary. The deployment supported a larger interdisciplinary field study investigating alternative water management practices for duck clubs to minimize production of methyl-mercury and BOD drainage to tidal sloughs. Seasonal water management practices for waterfowl production divert slough water and drain it back later with elevated dissolved organic carbon and associated biological oxygen demand. The more than one-year deployment allowed analysis of tidal to seasonal hydrodynamics and transport characteristics of these partially diked sloughs adjacent to managed waterfowl club wetlands. Results show how tidal flows and scalar transport are modified by this land use and also influenced by climate and conditions in the regional estuary.

Introduction

Dissolved oxygen in estuarine sloughs influences a variety of foodweb production processes including aerobic metabolism of bio-available carbon (Mitsch and Gosselink 1993). Managed wetlands in Suisun Marsh export dissolved organic carbon and associated biological oxygen demand in predictable seasonal patterns as a consequence of seasonal water management for waterfowl production (Miller et al. 1975). Some small sloughs adjacent to managed wetlands are sources for water and sinks for return flows with elevated biological oxygen demand. We deployed high frequency flow and scalar concentration sensors at the mouth of two tidal sloughs that are adjacent to managed wetlands to observe the integrated outcome of wetland drainage on slough temperature and dissolved oxygen. The study duration (approximately fifteen months) allowed observation of physical and geomorphological drivers including tides, spring-neap cycles, and diel/morphological affects on water temperature. Co-location of flow and scalar sensors allowed calculation of water and material fluxes to explain tidal slough behavior as shifting sources and sinks for water, temperature, and dissolved oxygen.

Peytonia and Boynton Slough description

Boynton and Peytonia Sloughs are tributaries to Suisun Slough in the northeast portion of Suisun Marsh (Figure 1). Both Sloughs are highly modified from their former function as third to fourth order channels of a dendritic tidal creek system. Boynton Slough is more modified as it is leveed completely for the approximately 3 miles between its confluence with Suisun Slough and the railroad. Beyond the railroad, the slough continues about ¾ mile in a small tidal marsh patch until it merges with an earthen canal that ultimately connects to the regional treatment plant outfall. Peytonia Slough is leveed only on its southern side from the confluence with Suisun Slough and the railroad track, about 2 miles distance. Beyond the railroad track, the system branches within a muted tidal marsh over less than 1/2 mile where it transitions upland to become Ledgewood Creek, a seasonally flowing stream that receives significant urban runoff from the Fairfield area. The land area north of Peytonia Slough is nominal tidal marsh with no levee. While tidal, this property (owned by the California Department of Fish and Game) is cut through with several linear ditches, mostly to limit ponding for mosquito control. Both sloughs exhibit similar average depths, approximately 3-5 meters over most of their length.

Methods

Current meters. Upward looking Doppler current meters were deployed near the entrances to Boynton Slough and Peytonia Slough between 9/14/2007 and 3/25/2008. The Boynton Slough site coordinate location was 38’ 12.614 N; 122’ 02.329 W. The Peytonia Slough site coordinates are 38’ 13.567 N; 122’ 02.395 W (Figure ??). We used Argonaut XR 3-beam current meters at both sites running at 1500 kHz. The current meters were attached to a “Frisbee frame” for stability. A 50 ft cable was laid on the bottom with a weight attached to the end, and a cable with a surface mark attached to the weight (Figure 2). The sampling period was 600 seconds and the averaging period was 240 sec. Attached communication and power cables were brought to shore and terminated in an environmental enclosure. The instruments were powered a 100 amp/hr battery placed within the enclosure.

At Boynton Slough, the stage-area rating was created from a discharge measurement collected at 1440 on 09/16/2008. The local datum was set to -5.92 (stage value 5.92 @ 1440), and the full range of stage values for record was used. Excel was used to generate the equation Area = 2.7304 * stg^2 + 76.278 * stg + 442.8. An index velocity rating was based on two sets of discharge measurements taken on 9/16/2008 and 2/4/2008. The mean channel velocity was determined to be 0.8420*Index Velocity + 0.0328. Appendix A contains a full summary of field notes and data processing for Boynton Slough. At Peytonia Slough, the stage-area rating was created from a discharge measurement collected at 1230 on 09/25/2008. The local datum was set to -5.41 (stage value 5.41 @ 1440), and the full range of stage values for record was used. Excel was used to generate the equation Area = 1.9166 * stg^2 + 69.451 * stg + 401.5. An index velocity rating was based on one set of 61 discharge measurements taken on 9/25/2008. The mean channel velocity was determined to be 0.8427*Index Velocity + 0.0041. Appendix B contains a full summary of field notes and data processing for Peytonia Slough.

Multi-parameter sondes. Sondes were co-located with the current meters so that constituent fluxes could be calculated (Figure 2). We used battery powered YSI 600 sondes deployed near mid-depth. Sondes were attached to steel cables and suspended from underwater buoys. 125 lb weights anchored the apparatus. Another 100 foot stainless steel cable connected the sonde apparatus to another weight that anchored a marker buoy. The YSI 600 was programmed to log dissolved oxygen (optical), temperature, specific conductance, and unvented depth, every 15 minutes. The sondes were serviced and data downloaded approximately once per month. Equipment failures that occurred were due to probe leakage, and bio-fouling.

Results

Tidal and tidally averaged (net) flow. Current profilers were deployed between September 17, 2007 and January 2, 2009 at Peytonia Slough, and between September 17 and February 28, 2009 at Boynton Slough. Figure 3 shows the tidal and net flow time series for both locations. The net flows were calculated using a digital low pass filter based on Walters (1995). The Peytonia Slough record includes a gap between August 8 and September 17, 2008 due to a battery cable failure. The Boynton Slough record includes a gap between November 14, 2008 and February 4, due to a battery failure. Boynton Slough tidal flows range between about -800 and +1200 cfs while Peytonia Slough tidal flows range between about -700 and +800 cfs. Both sloughs exhibit an ebb-dominant tidal flow pattern typical of modified sloughs as the largest magnitude tidal flows occur during full moons on ebb tides. Peak ebb flows on Peytonia Slough reach approximately 1400 cfs, peak ebb flows on Boynton Slough reach approximately 1500 CFS.

Figure 4 shows only net flows for both sloughs to highlight the seasonal pattern. Net flows are determined using a low-pass filter to remove oscillations at the tidal timescale. Variability in the Figure 4 signals is therefore due to climate, inflows, evaporation, and the lunar cycle. Both sites exhibit generally positive outflow flux in the winter months and negative outflow flux in the summer months. Winter positive outflows are due to watershed accretions during winter storms while summer negative outflows are likely due to evaporation and evapotranspiration. Higher frequency fluctuations are also present. For example, Boynton Slough exhibits strong upstream net flow beginning in late September 2007 and 2008 when duck clubs begin filling managed wetlands. Negative net flow in Boynton slough ramps up to around 70 cfs by September 21, 2008 and maintains this level of upstream net flow until around September 28, 2008. Spring-neap tide oscillations are also evident that, during the fall, determine whether the flux of flow is positive or negative.

Figure 5 shows net flow on both sloughs oscillating approximately with lunar maximums. Both sloughs are generally filling at a peak rate of 10-40 cfs around full and new moons, and draining similar volumes during lunar quarters. Figure 3 also includes barometric pressure that also exerts influence on net flow. Observed net flow is a superposition of uncorrelated lunar and barometric pressure forcing along with the seasonal timescale oscillation shown in Figure 2.

Both sites are driven strongly by barometric pressure. Figure 6 shows a low pressure event on January 4, 2008 when both sloughs responded first by rapidly filling. Flood tide flows spiked up to 1,000 to 1,200 cfs. Peytonia Slough flood flow spiked more than Boynton despite its slightly smaller size. This is likely due to the existence of tidal marsh in the Peytonia Slough watershed. The ensuing ebb tide exhibited drain flows about two times the volume of previous ebb tides.

Constituent time-series and fluxes

Water temperature. Figure 7 shows the complete temperature time series for both sloughs. The temperature sensor was maintained about mid depth (~2 meters off bottom) for the duration of the study. The seasonal pattern is similar though Boynton Slough is often slightly warmer. The winter temperature signal is driven by tidal flows, while summer temperature exhibits a superposition of diel heating/cooling and tidal influence. Winter storm events trigger significantly warmer water on ebb tide at Boynton Slough. Figure 8 shows the tidal timescale water temperature response before and after a significant storm on January 4th 2008. Late ebb tide water exits Boynton Slough spiked in temperature by ~2 degrees C. Peytonia Slough follows the same pattern with less magnitude. Prior to the storm, both sites exhibit the opposite pattern—the highest temperature occurs at the end of the flood tide. Boynton Slough processes storm water through the regional WWTP, possibly accounting for the larger post-storm temperature spikes.

Summer water temperature exhibits diel variability with maximum temperatures in the summer occurring in the late afternoon between 20 and 22 degrees C. The additional influence of tides generates different characteristics between the two sloughs (Figure 9). Peytonia Slough develops significantly lower temperatures on ebb tides during the strong spring tides in the summer. Summer high-high spring tides occur near midnight during the summer allowing water to flood available marsh plane. Boynton Slough is mostly diked and therefore remains within the channel while the Peytonia Slough watershed contains undiked land along its northern edge. High tide water spreads shallowly on the marsh plane and cools over night. The ensuing ebb tide carries the cooled water past the temperature sensor. By this mechanism, spring tide ebb water temperature is about 1 degree C cooler at Peytonia compared to Boynton Slough.

Figure 10 shows advective and dispersive components of temperature flux. Temperature flux (and all flux estimates to come) is calculated as

$$\underbrace{\langle Qt^*Ct \rangle}_{\text{Total flux}} = \underbrace{\langle Qt \rangle \langle Ct \rangle}_{\text{advective flux}} + \underbrace{\langle Q't^*C't \rangle}_{\text{dispersive flux}}$$

Where Qt and Ct are flow and temperature (or scalar) time series data, <> indicates low pass filter, and Q't and C't are deviations calculated as data minus filter. The top panel shows that most flux is advective. That is, temperature transport is controlled primarily by non tidal water motions. In late winter/early spring, both sloughs are generally a heat source as storm runoff from the watershed (filtered through the regional WWTP and urban areas) is warmer than Suisun Bay water. In late summer/early fall, the opposite is true. The sloughs are generally temperature sinks, especially on spring tides when water is cooled overnight on high tides (Figure 9). Closer examination shows that tidally averaged water temperature is generally cooler on spring tides (Figure 11). The upper and lower panels are as in Figure 10 and include lunar phase. Only tidally averaged temperature is shown because diel water and air temperature are tightly correlated in warmer months. The high-tide overnight cooling mechanism probably depends on presence of tidal marsh geomorphology in the slough system. Both sloughs have some relatively natural tidal marsh geomorphology. The Peytonia system is more than half tidal marsh (albeit modified) while the Boynton system has a several acre patch of tidal marsh west of the railroad.

Salinity (specific conductance). Figure 12 shows the complete 15-minute specific conductivity record for both stations. The data shows the typical annual pattern of lowest salinity following the first significant delta outflow event (around January 4 in 2008, after January 15 in 2009). Low salinity continues through May and rises with lower Delta outflow. Peytonia Slough maintains salinity levels 10-20% less than Boynton Slough throughout the record. This reflects the salinity gradient commonly observed along Suisun Slough—higher near the mouth, lower at its terminus at Suisun City. Tidal salinity variability follows a consistent pattern throughout the year. Figure 13 shows that low salinity always occurs at the end of ebb tide while high salinity always occurs at the end of flood tide. This reflects the just mentioned salinity gradient in Suisun Slough and freshwater input at the head of each slough. The salinity gradient is maximized in the fall when watershed creek input is increased by early rain but delta outflow has not yet increased. Salt flux is shown in Figure 14 for the study period compared to tidally averaged salinity. Salt flux is generally negative especially in late September and early October—the period that duck clubs are filling with channel water. Oscillations in salt flux are broadly correlated with the spring-neap cycle.

Dissolved oxygen. Figure 15 shows the complete dissolved oxygen time series. Trends and variability are generally consistent between the stations. Vertical green lines included to indicate sensor maintenance visit days. Depicting maintenance days indicates when dissolved oxygen variability is accounted for partly by bio fouling or other sensor problems. Expected low dissolved oxygen events occurred in late September 2007 and 2008 due to warm water and biological oxygen demand inputs from managed wetland drainage. Tidal cycle dissolved oxygen lows are always associated with the end of the ebb tide, highest values associated with the end of the flood tide. Figure 16 shows the associated flux of dissolved oxygen into the sloughs in fall (especially Boynton Slough). The sloughs are generally dissolved oxygen sinks in summer and Fall, and sources in winter and spring.

Discussion

Velocity and multi-parameter scalar sensors were deployed near the mouths of Boynton and Peytonia Sloughs in Suisun Marsh supporting a larger interdisciplinary field study investigating alternative water management practices for duck clubs to minimize production of methyl-mercury and BOD drainage to tidal sloughs. The more than one-year deployment allowed analysis of tidal to seasonal hydrodynamics and transport characteristics of these partially diked sloughs adjacent to managed waterfowl club wetlands. Results show how tidal flows and scalar transport are modified by this land use and also influenced by climate and conditions in the regional estuary.

Managed wetlands in Suisun Marsh export dissolved organic carbon and associated biological oxygen demand in predictable seasonal patterns as a consequence of seasonal water management for waterfowl production. The study duration (approximately fifteen months) allowed observation of physical and geomorphological drivers including tides, spring-neap cycles, and diel/morphological affects on water temperature. Co-location of flow and scalar sensors allowed calculation of water and material fluxes to explain tidal slough behavior as shifting sources and sinks for water, temperature, and dissolved oxygen. Results also show how tidal flows and scalar transport are modified by this land use and also influenced by climate and conditions in the regional estuary.

The sloughs have comparable size, drainage area, and tidal flow. We would expect them to generally dispersively flux material out of their respective systems because of the dominance of the ebb tide unless material is trapped for other reasons. The tidal flow velocity, reaching the 1 fps range each tide, is fast enough to almost fully evacuate the entire slough system each ebb tide. Indeed, the tidal range is more than half the depth in both sloughs. Therefore, materials like sediment and DOC from managed wetlands will be readily delivered to Suisun Slough where it can mix with the regional area. This process is mediated by both periodic and gradually oscillating processes. Figures 4 and 6 shows how water flux can be briefly but significantly affected by low barometric pressure events associated with storms. There is also a clear spring-neap tide oscillation evident in the filtered flow signal that can reach nearly 50 cfs, about 10% of the tidal magnitude (Figure 5). Seasonal climate can also mediate tidal exchange. Figure 4 suggests that net flows are positive in winter, and generally negative in Summer/early Fall when evaporation is an important net flow driver.

Drivers of water temperature can shift rather dramatically with changes in climate. During fair weather in winter, the warmest water temperatures occur at the end of flood tide suggesting a generally warmer Suisun Bay compared to creek influences. This pattern switches with the onset of a winter storm when the warmest temperatures occur at the end of ebb tide. Once switched, warmer ebb tide water tends to persist well into the next fair weather period (Figure 8). In contrast, summer water temperature responds rapidly to diel heating, though it is modulated significantly by tide status. Figure 9 also shows an approximately 2-week low frequency cycle in water temperature in both sloughs, possibly linked to the spring-neap cycle. One mechanism for this response could be the fact that spring-tide high tides are occurring over night, generally cooling water that is then returned on the following ebb tide in the early morning. Peytonia Slough develops significantly lower temperatures on ebb tides during the strong spring tides in the summer; ostensibly because it has a much higher percentage of its drainage area can be flooded by high tides. This mechanism could account for temperature oscillations at the tidal and spring-neap scale. It could also account for the observation that both sloughs are apparently a temperature sinks in summer/early fall (Figure 10). The primary flux component is advection, further suggesting that evaporation is fluxing both water and heat upstream. Figure 9 also shows that both sloughs become persistent sources of heat after the January 4 storm.

Seasonal salinity pattern is also instructive. Vegetation production is well-known to vary with soil salt content. Managed wetland operations are, among other things, attempting to manage diverted water to reduce soil salinity to improve plant productivity and diversity. However, Figure 14 suggests there is an overall flux of salt upstream as an annual average. The annual flux is clearly driven by summer and fall conditions when salt is imported upstream with the net flow. Much is returned over the winter months but at a slower rate. There also appears to be a significant difference between Peytonia and Boynton on this issue. Boynton, which is dominated by managed wetland operations, fluxes much more water and salt upstream in summer/fall. Peytonia is more or less balanced though the fall 2008 period shows slightly more tendency to flux salt upstream.

Managed wetlands in Suisun Marsh export dissolved organic carbon and associated biological oxygen demand in predictable seasonal patterns as a consequence of seasonal water management for waterfowl production. We recorded clear low DO signals timed with managed wetland drainage operations in the early fall and possibly with spring soil leaching drainage. DO is often below 5 mg/l on a tidally averaged basis meaning that conditions for most nekton is deleterious for extended periods.

Overall, the findings in this report are based on high frequency data that is ultimately time averaged to uncover general non-tidal, seasonal and annual patterns. Constituent monitoring including flow, salinity, temperature, and DO, allowed estimation of material loading rates that explain trends in constituent accumulation. There are also clear differences between the sloughs that appear to reflect relative position and land use. While our methods are well tested, flux estimation requires very high measurement precision in the high-frequency domain to assure accuracy of filtered results--the classic signal to noise problem. All reported flux estimates have a mechanistic basis and therefore engender confidence in their veracity. Future flux estimation should verify magnitudes of system response.

Appendix G-1
Boynton Slough current meter data summary and field notes

Site Location: 38' 12.614 N 122' 02.329 W

Instrument Information:
Argonaut XR 3-Beam — CPU Version: 11.6
Instrument SN: E891 — Frequency: 1500 kHz

Deployment Setup:
An Upward looking Argonaut XR was attached to a "Frisbee frame", a 50 ft cable was laid on the bottom with a weight attached to the end, and a cable with a surface mark attached to the weight. It was set to average for 240 sec, and to sample every 600 sec. See log files for more information. The instruments communications cable was brought to shore and the Argonaut XR was powered by a 100 amp/hr battery in an environmental enclosure.

Length of Deployment: 9/14/2007-3/25/2008

Pitch, roll, and heading remained consistent until the instrument was pulled, and the new pitch, roll and heading values remained consistent after that time period. The signal to noise ratio (SNR), which is a data quality indicator was good, expect for periods of record noted in the data processing forms, and in some cases data was deleted that was poor, and this was partially based on low to zero SNR values.

Stage values from a nearby DWR gage station was used to compute the final discharge. The water level data from the pressure sensor in the Argonaut XR is not accurate, without barometric corrections, because the sensor is not vented. The data from the pressure sensor is necessary to calculate time shifts between the gage station and the location of the instrument.

The data quality from 9/14/2007 – 11/14/2008 and 2/04/2009-03/25/2009 is considered **GOOD** because the calibration rating curve is statistically good.

Data Gaps:

Data Range	Parameter	Reason for Gap
01/05/2008 1710-2220	Velocity	Unusual velocity corresponds to dip in SNR
11/14/2008-02/04/2008	Velocity, Stage	Dead Battery @ site
02/07/2009 1610-2240	Velocity	Beam Blockage, SNR values drops to zero

Data Processing Steps:
1. Raw data from the instrument **.arg** files are viewed in ViewArgonaut software and those are exported as **.dat** files.

2. The **.dat** files are run through a **Matlab** script **boyconvertarg.m** which converts the file to a readable for the editing program **Gr**, and also corrects the velocity for principle flow directions. These directions are calculated by looking at the raw data file in **ViewArgonaut.**

3. The first two data files were recorded every 10 minutes, but the time did not occur at even 10 minute intervals. This data was run through a **Matlab** script **convert10min.m**, to shift the data to fall every 10 minutes after the hour (10, 20, 30, 40, 0). The output file was a **…converted.txt** file.

4. The discharge measurements are processed in WinRiverII, and the discharge summary table is exported. This **.xls** file as well as the edited index velocity file, **.gr** file, is run through a Matlab script, **interpdata.m**. This script takes in both data files and interpolates the index velocities based on the mean timestamp of the discharge measurements, and outputs a **.txt** to run a linear regression on.

5. **Matlab** script **linfit.m** is used to develop an linear regression of index velocity an mean channel velocity, and outputs a graph with equation.

6. Stage-Area is calculated in a program called **AreaComp**, that reads in a **WinRiver** file and develops a relationship between the cross sectional area and stage. This data is copied into an excel spreadsheet and a polynomial equation is used.

7. The last step is to run the edited data files **.gr** through the Matlab script **boyfinalcomp.m**, using the calculated index velocity rating and the stage area rating to calculate final Q's. Outputs a **.csv** file containing stage, index velocity, calculated velocity, and discharge.

Time Drift Corrections

1. The Argonaut at this site showed an increasingly large drift in its internal clock, therefore most of the data files had to have a time correction applied to them.

2. The **Matlab** script **timedriftcorrection.m,** takes an edited .gr file and prorates the timestamp according to the time drift for that data set and then interpolates the stage and velocities for the original timestamp based on the corrected timestamp (adjusted for time drift). The data quality indicators are not adjusted however. Output file is **corrected.gr**

3. Files were corrected based on a clock drift of over 2 minutes. The following dates and the associated time drift are as follows:

11/16/2007 – 01/22/2008	140 sec slow
01/22/2008 – 05/09/2008	270 sec slow
05/09/2008 – 9/16/2008	360 sec slow
09/16/2008 – 11/14/2008	213 sec slow
02/05/2008 – 03/25/2008	150 sec slow

Editing Stage Data
1. **Matlab** script **readstagefile.m** was used to convert the data file to a readable file in **Gr**, output is a **.txt** file.

2. The stage from DWR gage station had to be adjusted +10 minutes to line up with the stage from the Peytonia Slough site, and was used in lieu of the stage data from the pressure sensor.

3. Data from the Argonaut pressure sensor was used from 03/10/2009 1210 – 03/17/2009 1010, because there was no data available from the DWR gage station.

Stage Area Rating
Stage Area Rating was created from discharge measurement file PEY025 that was collected @ 1440 on 09/16/2008. The program AreaComp was used to develop the relationship. The datum was set to -5.92 (stage value 5.92 @ 1440), and the full range of stage values for record was used. Excel was used to create the following equation: **Area = 2.7304 * stg^2 + 76.278 * stg + 442.8**

Index Velocity Rating
Two sets of discharge measurements were taken, on 9/16/2008 and 2/4/2008 to develop and index velocity rating as follows: **Mean Channel Velocity = 0.8420*Index Velocity + 0.0328**

Field Notes Summary:
Site was visited 8 times on 9/14/2007, 10/19/2007, 11/16/2007, 1/22/2008, 5/09/2008, 9/16/2008, 2/4/2009 and 3/25/2009. Attached are scan copies of field notes.

Throughout the deployment the site maintained consistent pitch and roll values. On 11/16/2007, 6 data files were recovered from last deployment, indicating that there might have been power losses. Downward looking ADCP calibration measurements were taken on 9/16/2008, and 2/4/2009. On 2/4/2009 it was discovered that the battery had died on 11/14/2008. The instrument was pulled on 3/25/2009.

Appendix G-2
Peytonia Slough current meter data summary and field notes

Site Location: 38’ 13.567 N**;** 122’ 02.395 W

Instrument Information:

Argonaut XR 3-Beam	CPU Version: 11.6
Instrument SN: E1061	Frequency: 1500 kHz

Deployment Setup:
An Upward looking Argonaut XR was attached to a “Frisbee frame”, a 50 ft cable was laid on the bottom with a weight attached to the end, and a cable with a surface mark attached to the weight. It was set to average for 240 sec, and to sample every 600 sec. See log files for more information. The instruments communications cable was brought to shore and the Argonaut XR was powered by a 100 amp/hr battery in an environmental enclosure.

Length of Deployment: 9/14/2007-1/02/2009

Field Notes Summary:
Site was visited 9 times on 9/14/2007, 10/19/2007, 11/16/2007, 1/22/2008, 5/09/2008, 9/16/2008, 9/17/2008, 9/25/2008, and 3/25/2009. Attached are scan copies of field notes.

Throughout the deployment the site maintained consistent pitch and roll values. On 9/16/2008 it was discovered that the communications cable had been cut, and the instrument was pulled up and the communications cable was replaced on 9/17/2008. Downward looking ADCP calibration measurements were taken on 9/25/2008. On 3/25**/**2009 the instrument was pulled.

Data Summary:
Pitch, roll, and heading remained consistent until the instrument was pulled, and the new pitch, roll and heading values remained consistent after that time period. The signal to noise ratio (SNR), which is a data quality indicator was good, expect for periods of record noted in the data processing forms, and in some cases data was deleted that was poor, and this was partially based on low to zero SNR values.

Stage values from a nearby DWR gage station was used to compute the final discharge. The water level data from the pressure sensor in the Argonaut XR is not accurate, without barometric corrections, because the sensor is not vented. The data from the pressure sensor is necessary to calculate time shifts between the gage station and the location of the instrument.

The data quality from 9/14/2007 – 8/7/2008 is considered fair since the Argonaut XR had to be pulled from its original location before a calibration rating could be made. The data from 9/17/2008 – 1/02/2009 is considered good because the calibration rating curve is statistically good. With that said the data before and after the instrument was pulled correlates with the Boynton Slough site well, and the instrument was redeployed in about the same spot and maintained less than a 5 degree pitch and roll at all times.

Data Gaps:

Date Range	Parameter	Reason for Gap
11/26/2007 1410-1700	Velocity	Beam Blockage
05/09/2008 0200-0550	Velocity	Data Questionable, did not trend with BOY data, it was deleted
08/07/2008 @ 2300 – 09/17/2008 @ 1150	Velocity and Stage	Comm Cable Cut

Data Processing Steps:

1. Raw data from the instrument **.arg** files are viewed in ViewArgonaut software and those are exported as **.dat** files.

2. The **.dat** files are run through a **Matlab** script **peyconvertarg.m** which converts the file to a readable for the editing program **Gr**, and also corrects the velocity for principle flow directions. These directions are calculated by looking at the raw data file in **ViewArgonaut.**

3. The first two data files were recorded every 10 minutes, but the time did not occur at even 10 minute intervals. This data was run through a **Matlab** script **convert10min.m**, to shift the data to fall every 10 minutes after the hour (10, 20, 30, 40, 0). The output file was a **…converted.txt** file.

4. The discharge measurements are processed in WinRiverII, and the discharge summary table is exported. This **.xls** file as well as the edited index velocity file, **.gr** file, is run through a Matlab script, **interpdata.m**. This script takes in both data files and interpolates the index velocities based on the mean timestamp of the discharge measurements, and outputs a **.txt** to run a linear regression on.

5. **Matlab** script **linfit.m** is used to develop an linear regression of index velocity an mean channel velocity, and outputs a graph with equation.

6. Stage-Area is calculated in a program called **AreaComp**, that reads in a **WinRiver** file and develops a relationship between the cross sectional area and stage. This data is copied into an excel spreadsheet and a polynomial equation is used.

7. The last step is to run the edited data files **.gr** through the Matlab script **peyfinalcomp.m**, using the calculated index velocity rating and the stage area rating to calculate final Q's. Outputs a **.csv** file containing stage, index velocity, calculated velocity, and discharge.

Editing Stage Data

1. **Matlab** script **readstagefile.m** was used to convert the data file to a readable file in **Gr**, output is a **.txt** file.

2. The stage from DWR gage station had to be adjusted +10 minutes to line up with the stage from the Peytonia Slough site, and was used in lieu of the stage data from the pressure sensor.

Stage Area Rating
Stage Area Rating was created from discharge measurement file PEY025 that was collected @ 1230 on 09/25/2008. The program area comp was used to develop the relationship. The datum was set to -5.41 (stage value 5.41 @ 1230), and the full range of stage values for record was used. Microsoft Excel was used to create the following equation:

Area = 1.9166 * stg^2 + 69.451 * stg + 401.5

Index Velocity Rating
One set of 61 discharge measurements were taken, on 9/25/2008 to develop an index velocity rating as follows:

Mean Channel Velocity = 0.8427*Index Velocity + 0.0041

References

Miller AW, Miller RS, Cohen HC, Schultze RF, 1975. Suisun Marsh Study. USDA Soil Conservation Service, Davis, Ca.

Mitsch WJ, and JG Gosselink, 1993. Tidal freshwater marshes (chapter 9), pp. 267-291. In: Wetlands, 2nd edition, Van Nostrand Reinhold, New York.

Walters R.A. and J.W. Gartner, 1985. Subtidal sea level and current variations in the northern reach of San Francisco Bay. Estuarine, Coastal and Shelf Science. **21**, 17-32.

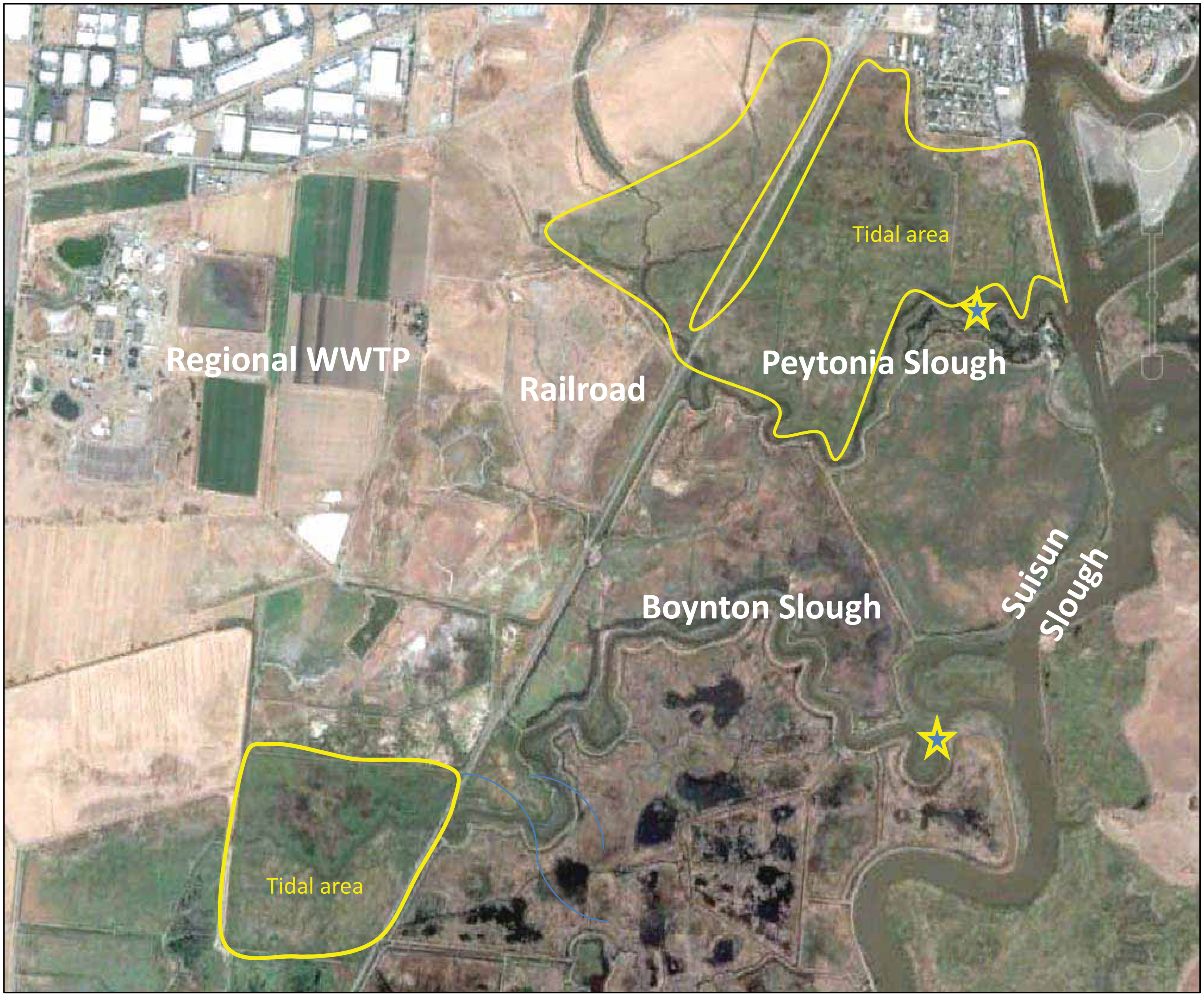

Figure 1. Aerial image of Boynton and Peytonia Sloughs in northwest Suisun Marsh. Stars indicate location of co-placed current meters and multi-parameter sondes. The tidal portions of each slough system are delineated.

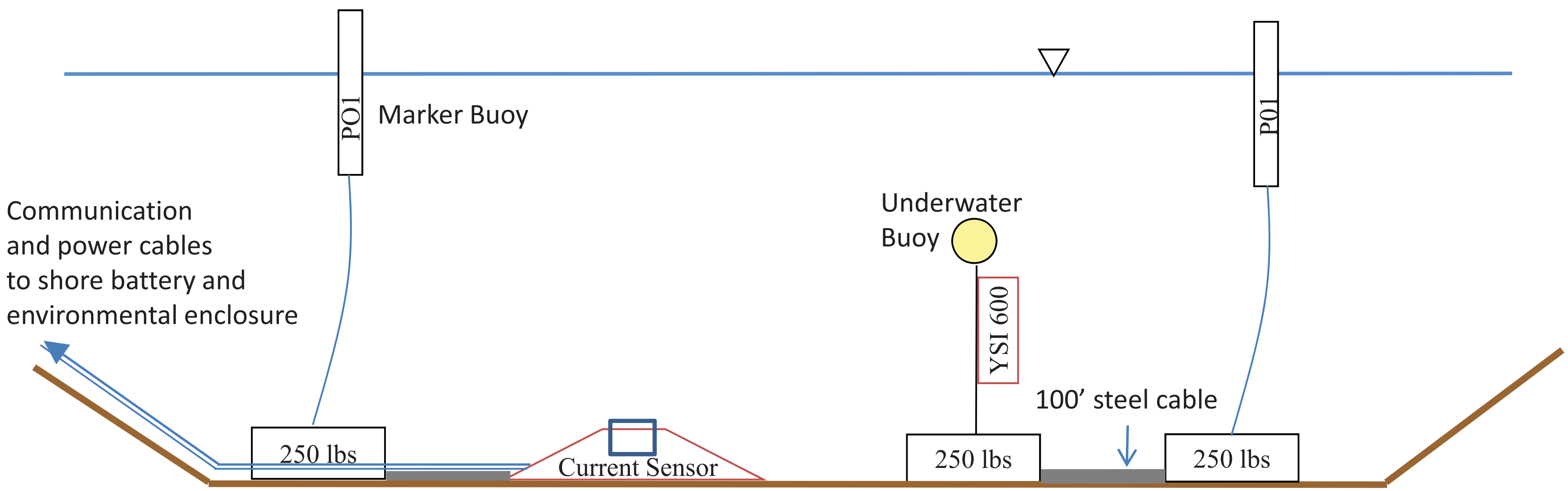

Figure 2. Instrument configuration in cross-section at mouths of Boynton and Peytonia Sloughs

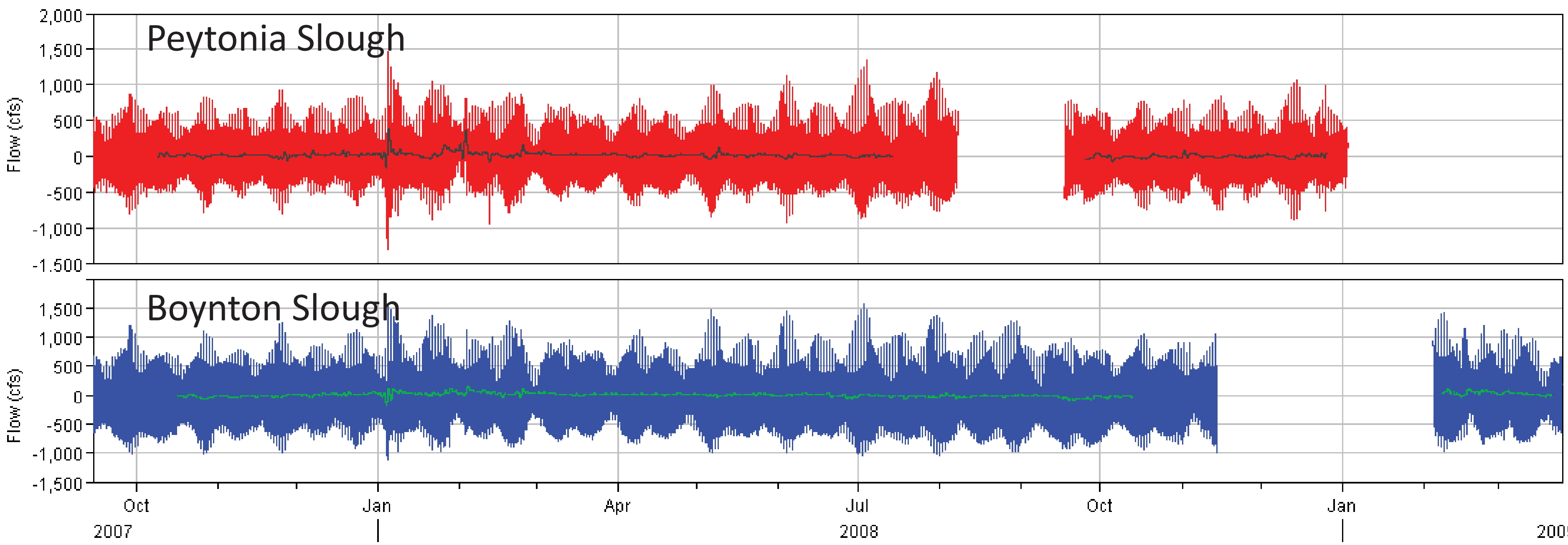

Figure 3. Tidal and net flow time series for the period of the study- September 2007—March 2009

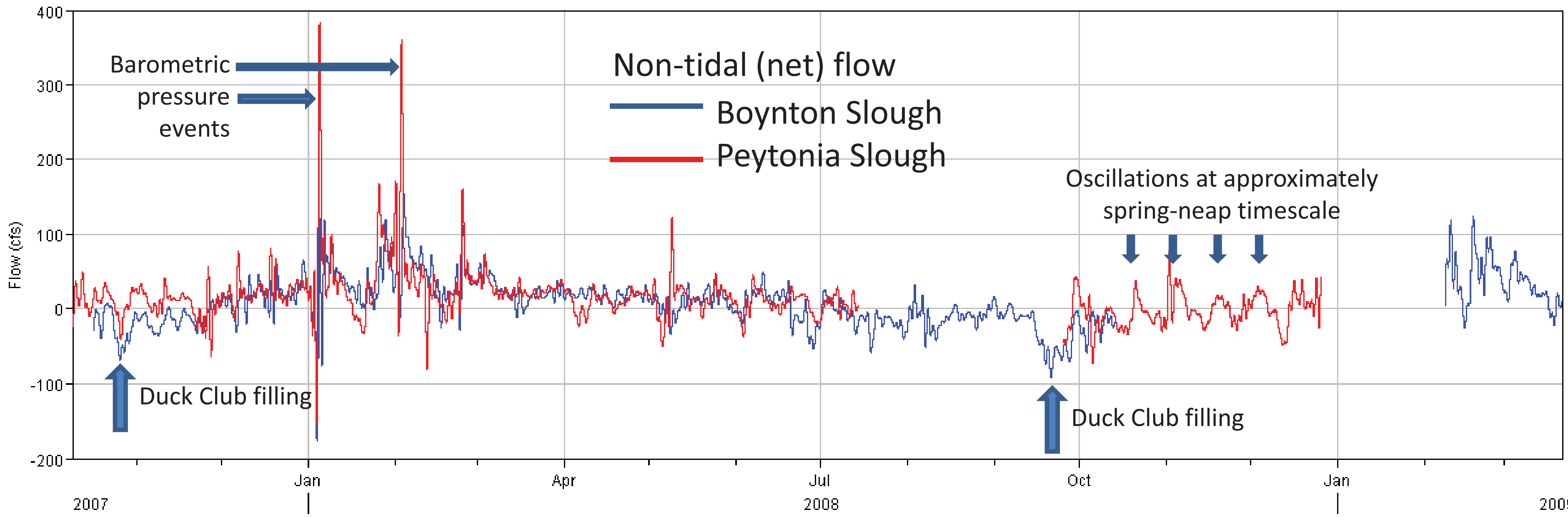

Figure 4. Digital low-pass filter of tidal flow time series- September 2007 – March 2009. Peytonia Slough (red), Boynton Slough (blue). Net flow oscillations are attributed to a superposition of season sea-level, barometric pressure, spring-neap lunar cycle, and managed wetland operations.

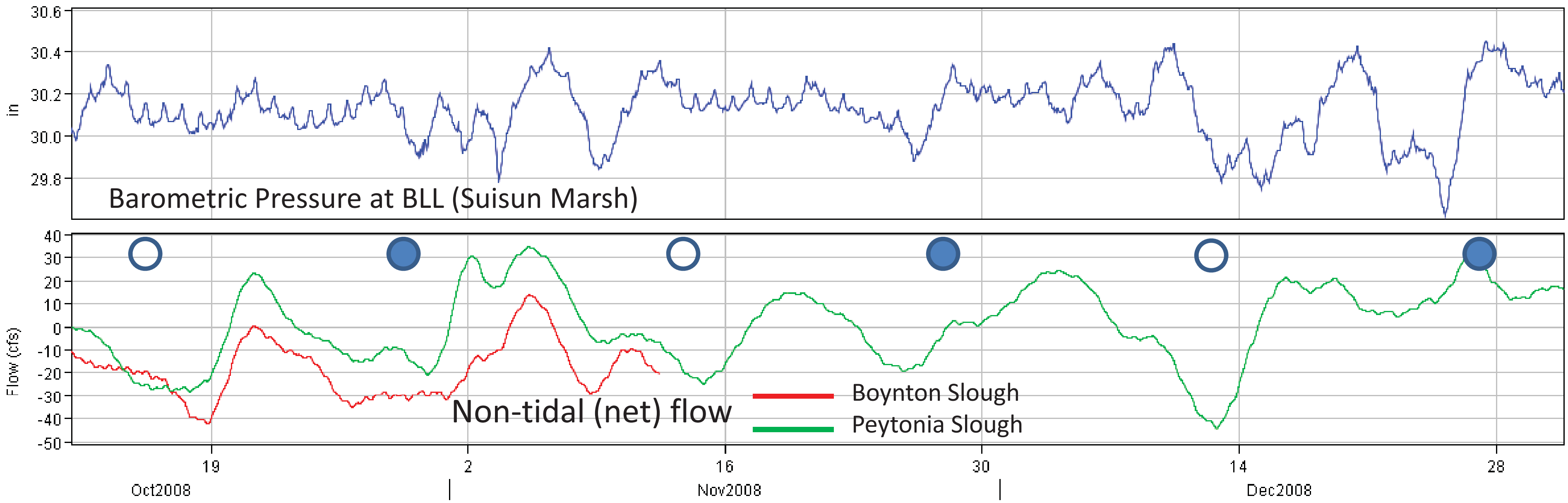

Figure 5. Net flow is influenced by moon phase and barometric pressure. Top panel shows barometric pressure, bottom panel shows net flow at Boynton and Peytonia Sloughs. Full and new moon phases are also shown.

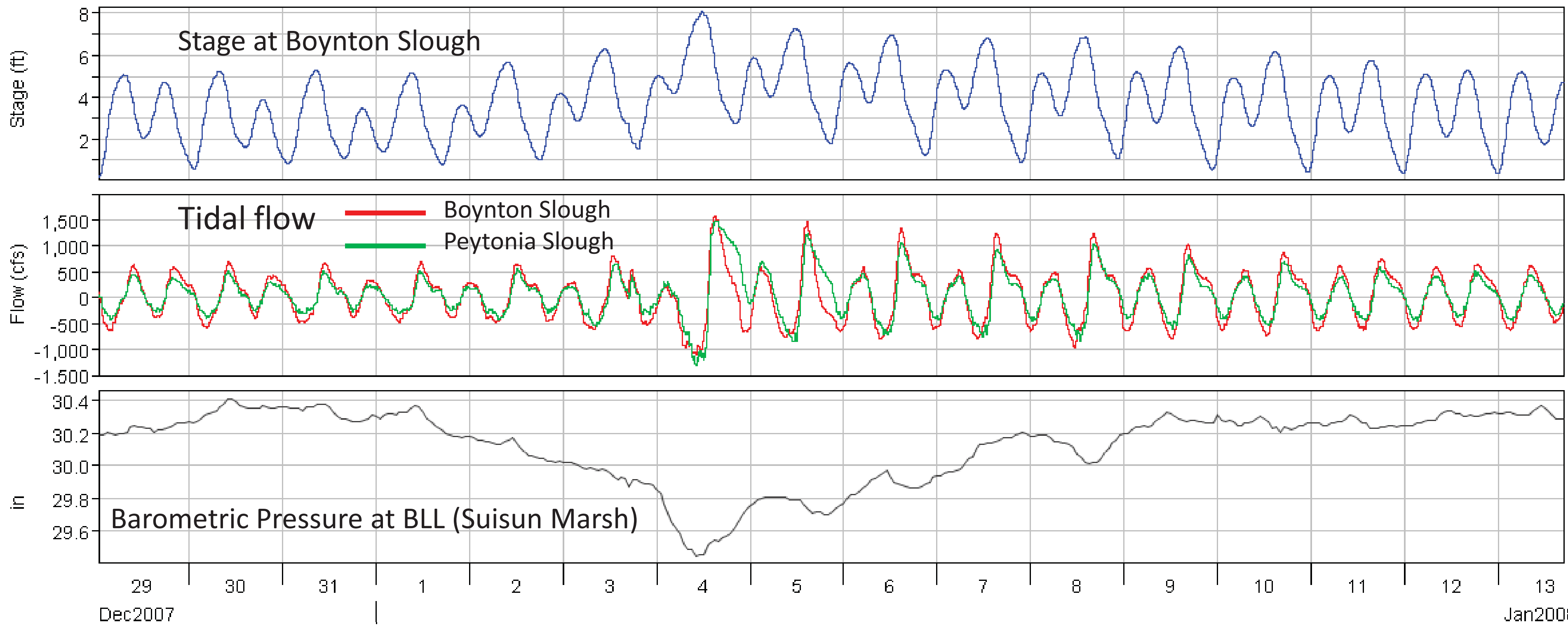

Figure 6. Tidal flow response to low pressure event on January 4, 2008.

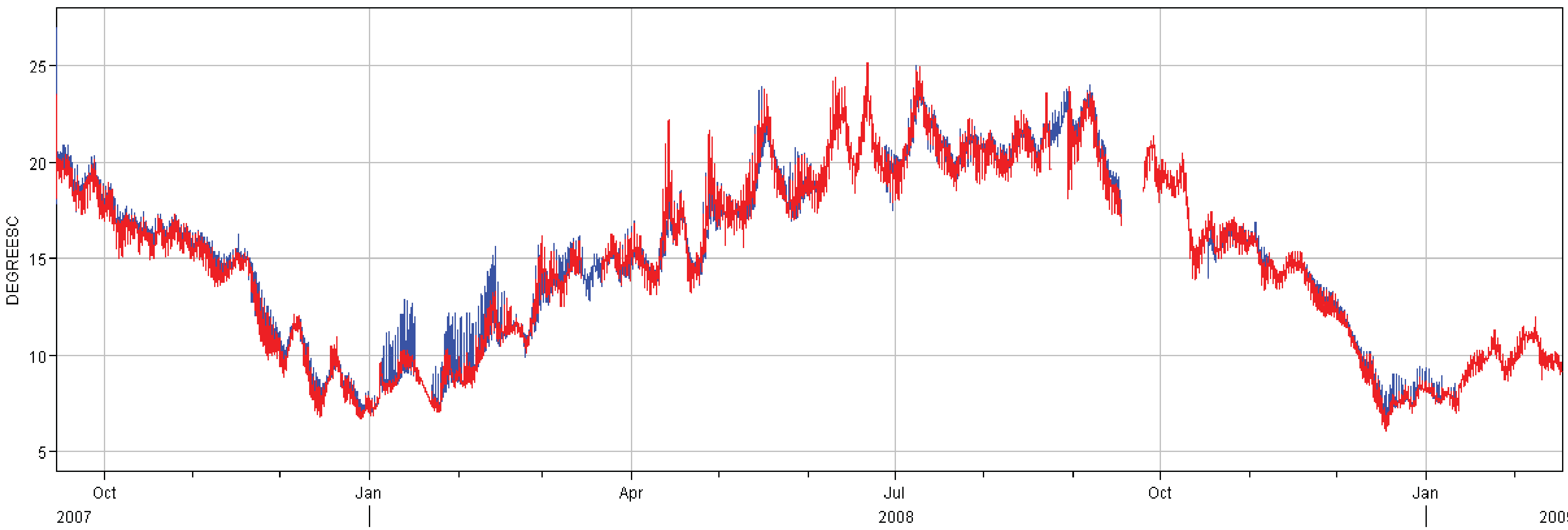

Figure 7. 15-minute temperature time series. Water temperature was sensed at approximately mid-depth.

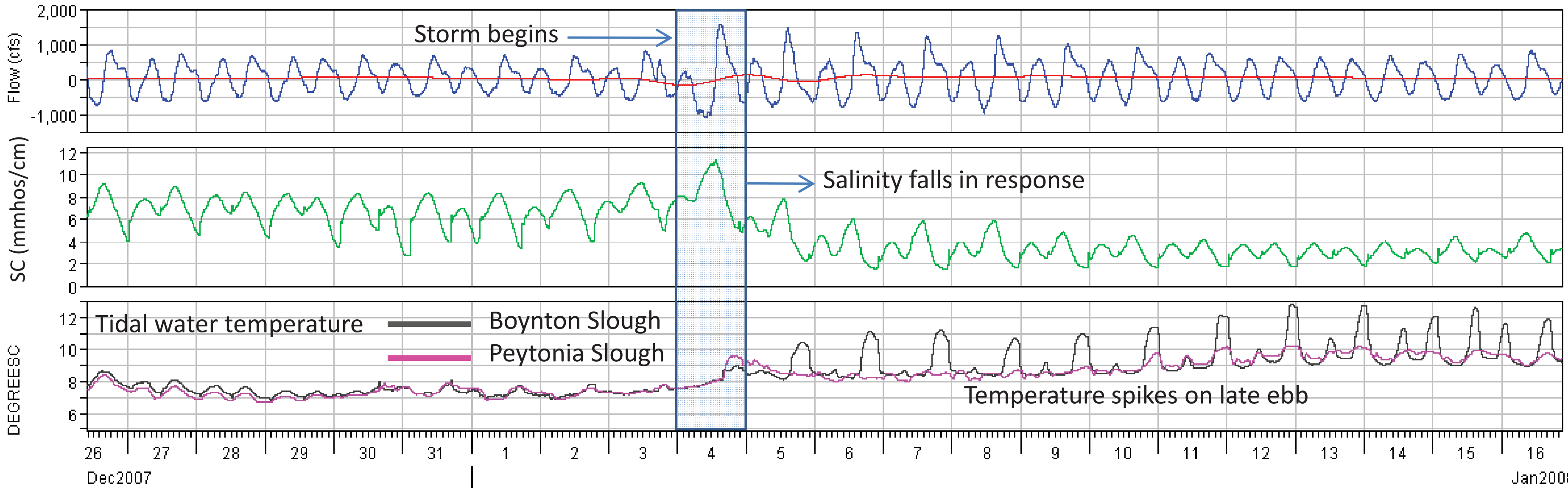

Figure 8. Effect of winter storm event on temperature at Boynton Slough. Significant rain occurred on January 4th. Thereafter, Late ebb tide water is ~2 degrees C warmer. Peytonia Slough follows a similar pattern with smaller magnitude change. Prior to the storm the highest temperature occurs at the end of the flood tide at both sites.

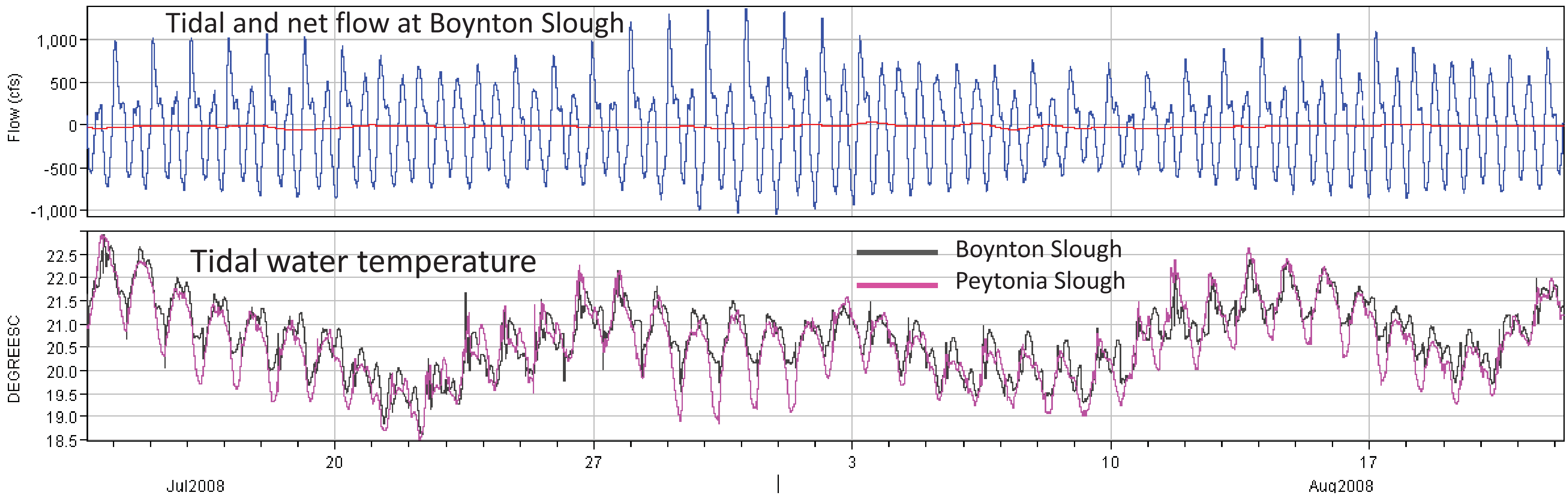

Figure 9. Tidal water temperature at Boynton and Peytonia Slough with tidal stage. Chart shows the difference between temperature response of ebb flows during spring tides. Expanded temperature variability at Peytonia is assumed to be from overnight cooling of water spread on to tidal marsh plane.

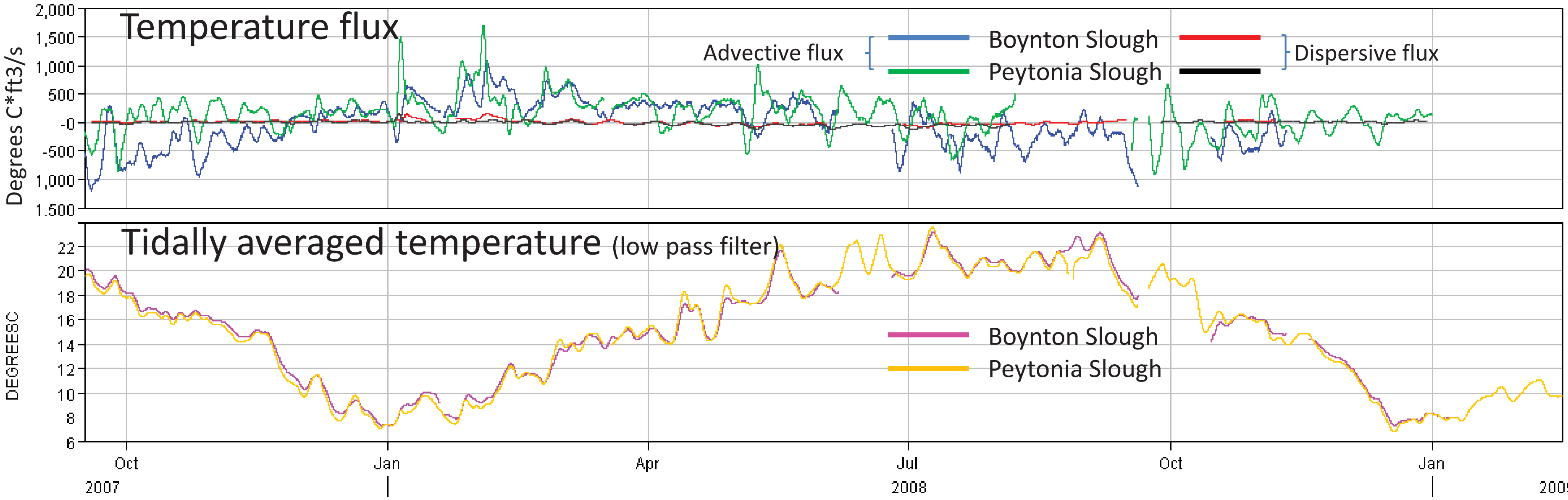

Figure 10. Temperature flux. Top panel shows advective and dispersive flux components for Boynton and Peytonia Sloughs. Bottom panel shows tidally averaged temperature over the period of the study.

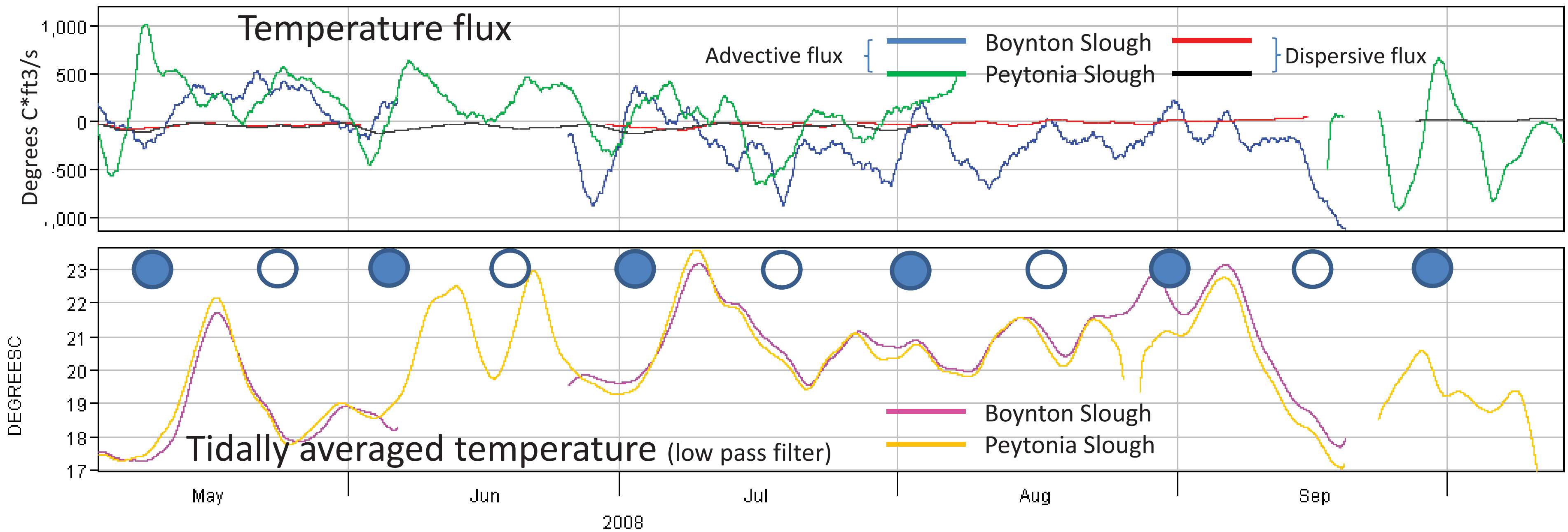

Figure 11. Temperature flux and non-tidal temperature response to lunar phase. Top panel shows advective and dispersive flux components for Boynton and Peytonia Sloughs. Bottom panel shows tidally averaged temperature over the period of the study with moon phase depicted.

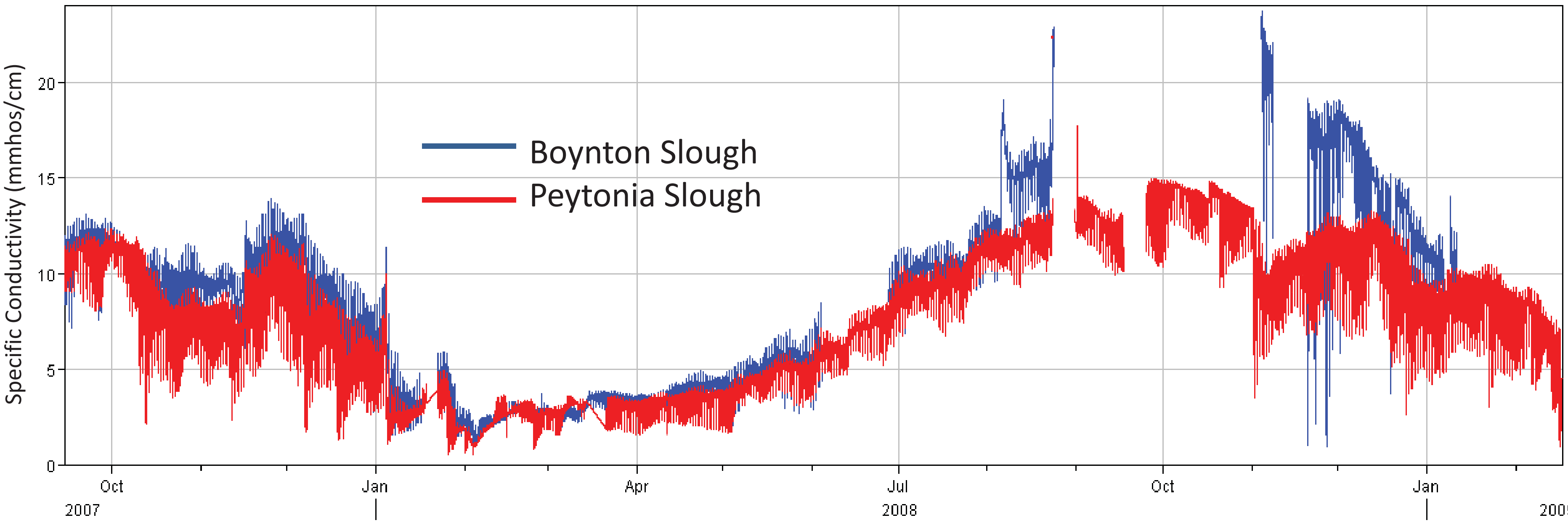

Figure 12. 15-minute specific conductivity at Boynton Slough and Peytonia Slough between September 15, 2007 and January 12, 2009.

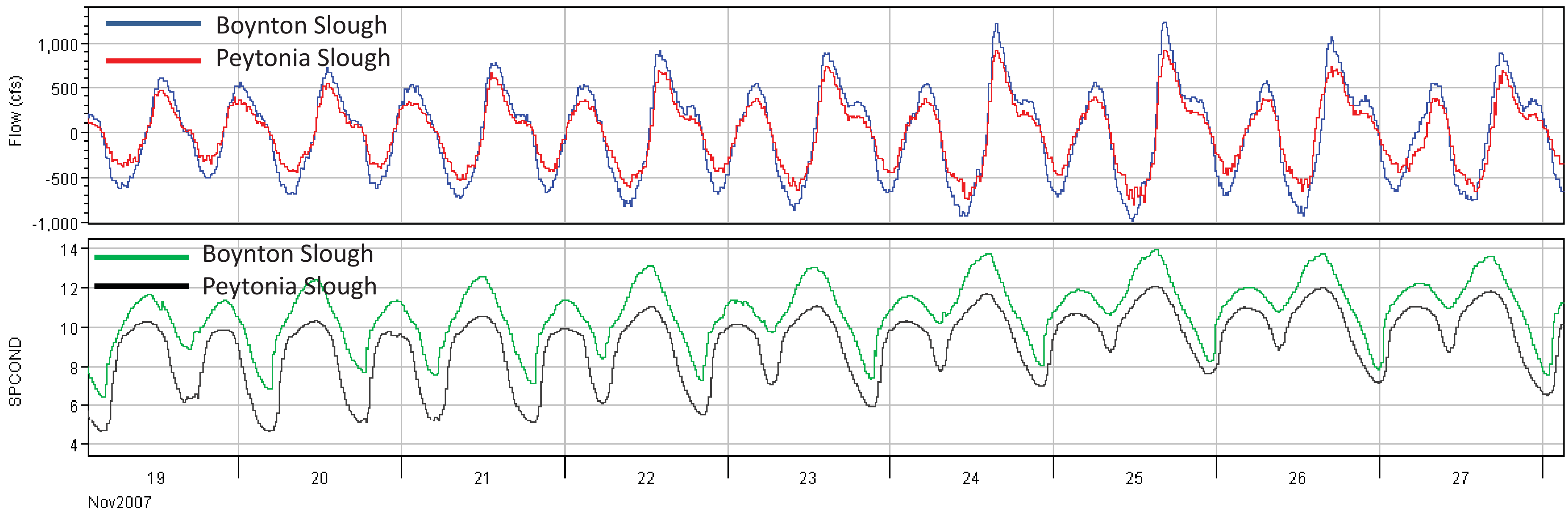

Figure 13. Tidal salinity phasing with tidal flows. High salinity occurs at the end of flood tide, low salinity occurs at the end of ebb tide.

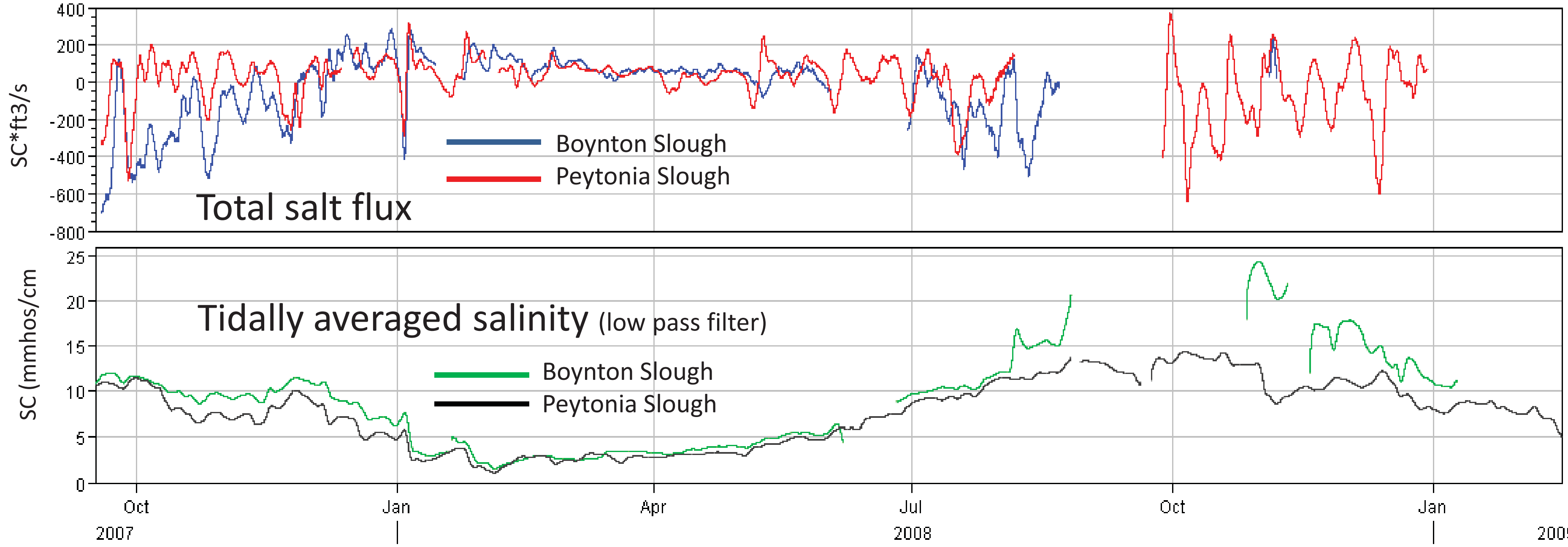

Figure 14. Total salt flux (advective plus dispersive) and tidally averaged salinity for the study period at Boynton and Peytonia Sloughs.

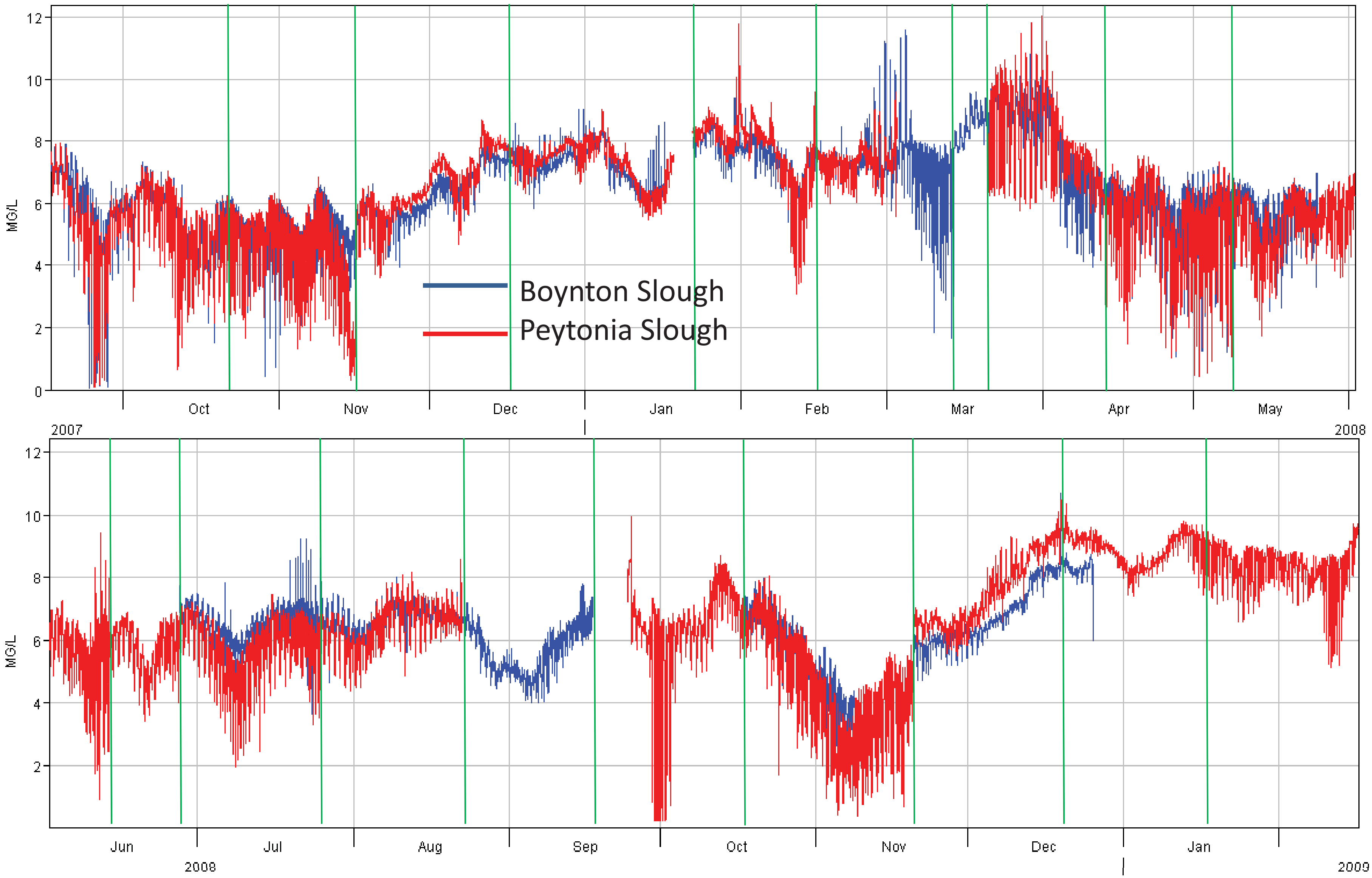

Figure 15. Complete dissolved oxygen concentration time series for Boynton and Peytonia Sloughs. Vertical green lines indicate sensor maintenance visit day for clues about DO response characteristic. Some results are influenced by bio-fouling or other malfunction.

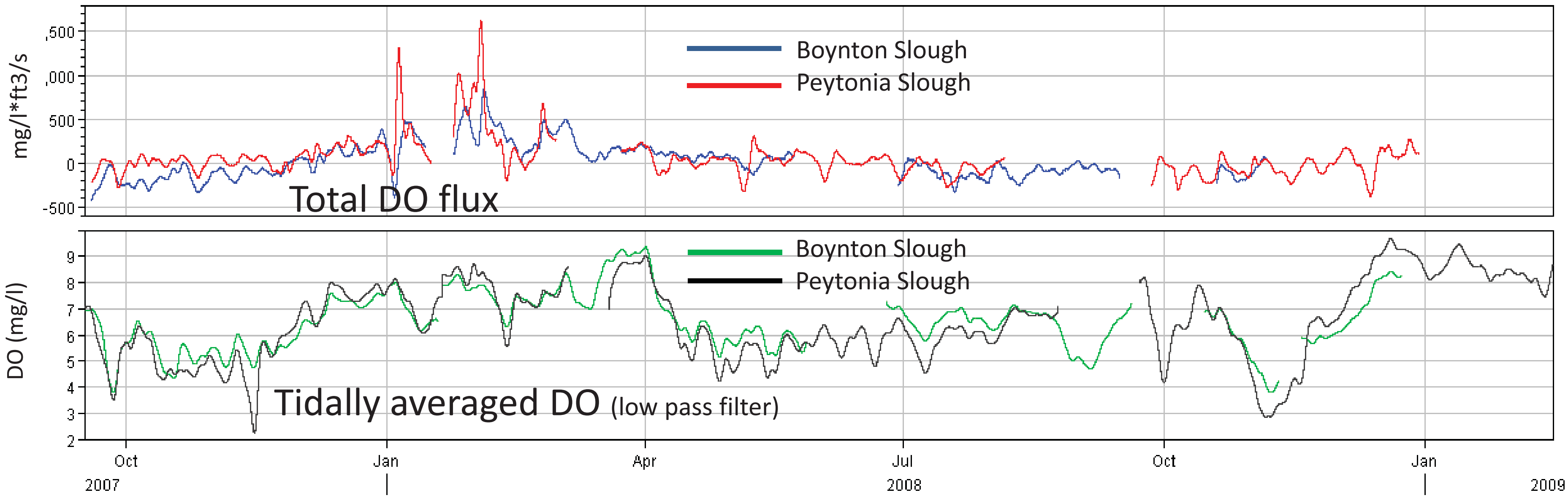

Figure 16. Dissolved oxygen flux with tidally averaged dissolved oxygen concentration.